BREADFRUIT (*ARTOCARPUS ALTILIS*): THE IMPACT OF ENVIRONMENT ON NUTRITIONAL COMPOSITION AND IMPLICATIONS FOR HAWAIʻI COMMUNITIES

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAIʻI AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

TROPICAL PLANT AND SOIL SCIENCES

JULY 2019

By Amber Mei Lan Waiokeola Needham

Thesis Committee:
Noa Lincoln, Chairperson
Rajesh Jha
Theodore Radovich
Alyssa Cho

Keywords:
Artocarpus altilis; Breadfruit; consumer survey; environmental variables; human nutrition

Acknowledgements

He wahi leo mahalo kēia i kuʻu ʻohana, ke akua, nā ʻaumākua a me kuʻu kūpuna ʻāina e mālama mau mai ka wā hūpēkole ʻānō. Eia nō au, he pūkoʻa kani ʻāina, he māmakakaua o kēia paio hoʻoluluhi nei o ka hele kulanui. He kauoha mana loa kēia e hōʻike ai i ka ʻike, ka ikaika, ke akamai, ka maopopo pono, ka ʻike pāpālua, a me ka mana o ka Hawaiʻi; pēlā nō ā i ke aloha ʻāina hope loa. Paʻi ka lima! Paʻi ka lima! Paʻi ka lima! Eō!

Many thanks to my committee members for their patience and willingness to guide me through this research. A special thank-you is due to Dr. Jha for his nurturing nature and allowing me use of his laboratory for my analyses. Each farmer and his/her family, who have participated openly in this study and in other breadfruit studies that have directly supported this research, are greatly appreciated as ultimately this compilation of time and energy has been for and with them. An incredible amount of support was given to me and this research by members of the Indigenous Cropping Systems Lab, the Jha Lab, Native Hawaiian Student Services, Maui Nui Botanical Gardens, Dr. Michael Kantar and the faculty and staff of the Department of Tropical Plant and Soil Sciences.

This work was supported, in part, by the USDA National Institute of Food and Agriculture, HATCH project 8035-H managed by the College of Tropical Agriculture and Human Resources and the Western SARE Research and Education grant.

Abstract

Breadfruit (*Artocarpus altilis*) is an evergreen tree of the Moraceae family that produces large starchy fruits. It is a highly productive and long-lived tree crop that has the potential to contribute greatly to human and environmental health and well-being. The crop is known to aid in soil retention and soil carbon sequestration as an agroforestry component, and is rich in carbohydrates (starch, resistant starch and fiber), specific amino acids and some vitamins and minerals. As breadfruit gains interest among local communities around the world for its many nutritional and environmental benefits, it has become important to understand several components of the fruit and its growing environments.

This project aimed to examine the effect of climate and soil variables on nutritional qualities of breadfruit. Three related studies were conducted: a meta-analysis of previous data sets, laboratory analyses of fruit nutrition, and a consumer survey. In the first, globally-comprised nutritional studies in breadfruit were collected and location of each study was used to extract climate and soil data using GIS software. Nutritional qualities of raw, mature breadfruit were analyzed by study site in order to examine the effects of varying abiotic factors – namely climate and soil. Findings indicate that climate and soils affect categories of breadfruit nutrition in different ways. Precipitation and cation exchange capacity of soil are significant influencers to nutritive aspects of breadfruit, especially the level of vitamins and to a lesser degree of proximate nutrients (protein, fat, fiber, energy, ash and moisture); in general, macro- and micro-nutrients were unaffected by climate and soil variables.

Following the global review, a Hawaii-based study was conducted with the objective of using Hawaii's diverse microclimates to further explore the effects of the abiotic environment on breadfruit nutrition; it was hypothesized that these small yet significant differences from place to place may have noteworthy effects on breadfruit nutritional value. Sample fruit from 48 different farms across four of the Hawaiian Islands were collected and analyzed first for nutrient composition. A parallel study derived soil and climate data for each site, from which I utilized data. Cultivar type played a large role in nutritional values. Overall results showed similar trends as those found among the globally-represented data. Proximate nutrients were affected by climate, however in this case soil characteristics played a more significant role. Furthermore, multivariate analysis showed that climatic variables and soil characteristics combined displayed

the most significance in terms of influencing nutritional variation. Macro- and micro-nutrients, again, were overall unaffected by either set of environmental variables.

Lastly, a consumer survey was created and administered to Hawai'i residents in order to gain insight into how local people are interacting with the fruit. Questions were crafted around consumption patterns, preparation methods, and health benefit awareness. Findings showed that on average people will eat about 13 servings of breadfruit per year, but with a large standard deviation and a distribution that demonstrates exponential decay. Essentially, vast majority of people eat breadfruit three times per year or less, but a few people eat a lot of it which results in an average value that is a bit deceiving. The survey also indicated that a person will eat about one quarter of a whole fruit in one sitting (per meal). Fruit are prepared mostly by steaming, baking, and frying. About 43% of respondents were aware of some type of health benefit associated with consuming the fruit. One of the most determining factors to overall consumption was having a backyard tree; people with their own tree ate about twice as much breadfruit as those who do not. Nearly 71% of respondents rely on a backyard tree for obtaining fruit – either their own or a family member's or friend's tree. Conversely, only 5% of consumers ever obtain fruit from a market. In addition, open-ended comment boxes were often used by participants to interject the difficulty in finding fruit (sources). This provides some insight into how breadfruit consumption can be improved as well as brings to attention the issue of accessibility to breadfruit sources.

Table of Contents

Forward

As a *kupa'āina*, it has been my goal and intent to carry out this work for Hawaiian people; for their longevity in health, culture and resilience in ever-changing times. A consistent influx of foreign influence makes Hawai'i a unique place rich in several cultures today. The importance of Hawaiian practices, however, and thus the foundational components of practice such as complex and efficient agrarian systems, have simultaneously been displaced over time. Breadfruit has a long history of being carried across seas by hand and canoe of my ancestors, and theirs too, playing a large role in population sustenance especially in areas where the classic staple of taro (*kalo; Colocasia esculenta*) was not grown in mass quantities. As the urgency of food security heightens in the face of climate change for our small and isolated island chain, I hope that breadfruit's potential in agriculture, health and well-being, can be seen as a practical prospect for Hawaiian people as well as local communities. Although the objectives of this research are specific, my underlying motive is for more indigenous crops to the Hawaiian Islands to continue to be studied with good intentions and their perpetuity emphasized. Health impairment, dispossession of land, food insecurity and capitalism in Hawai'i are all interconnected; though I cannot say that improving the body of knowledge for breadfruit will act as a solution to some of these issues, I am hopeful that addressing one of them (food) can fuel people to invest in the others.

Chapter 1

Introduction

1.1 Breadfruit Description, Morphology and Origin

Artocarpus altilis, commonly called breadfruit, is an evergreen tree of the Moraceae family that produces large starchy, carbohydrate-rich fruits. It is a fast-growing deciduous tree, able to grow up to 20 meters in height and slightly over one meter in diameter (Sikarawr et al., 2014). Yield has known to vary vastly between the Carribbean, South Pacific, and other regions; one breadfruit tree is capable of producing anywhere from 200-400 kilograms of fruit anually yet sometimes as little as 50 kilograms (Lincoln et al., 2018; Ragone, 1997). Though productivity may vary this way, the tree is known to be long-lived, giving fruit for several years.

Breadfruit and its relatives, *A. camansi, A. mariannensis* and hybrids between *A. mariannensis and A. altilis*, can be seeded and seedless. Due to domestication of the crop over time, and genetic selection for favorable tree traits, several of the *A. altilis* cultivars were and are seedless; propagation by seed is difficult and likely took place for wild ancestor trees, however vegetative propagation is most commonly used today (Ragone, 1997). A vegetatively propagated breadfruit tree, typically from a root shoot, can bear fruit within 3-6 years of establishment; if the tree is grafted, one can expect fruit within 2-3 years of establishment (Ragone, 1997). There are two seasons for fruit-bearing: one during rainy and hot summer months, and another, often smaller season, three to four months following (Ragone, 2011). Analysis by Jones et al. (2010) suggests that the onset of the fruiting season in most locations approximately occurs during the sun's zenith; however, cultivars that have adapted to certain places and are cultivated elsewhere may be capable of retaining their compatibility, potentially yielding year-round production.

Over the last three thousand years the fruit tree has travelled across the Pacific, becoming the staple food for many island nations and cultivated in tropical and subtropical regions (Ragone, 1997).

1.2 Crop Uses and Importance

The most commonly eaten plant part is the starchy flesh of the breadfruit fruit, which is prepared mainly by steaming, baking, frying and boiling (see Chapter 4; Roberts-Nkrumah and Badrie, 2005; Zerega et al., 2005). *A. altilis* will sometimes have large seeds within the flesh and, like that of the breadnut, a relative which has many seeds compared to the few of breadfruit, they can be roasted or boiled and eaten as well (Zerega et al., 2005). The fruit are eaten at all levels of maturity; juveniles may be pickled, slightly under-ripe fruit are preferable for the aforementioned preparation methods, and overripe fruit are compared to pudding in consistency and sweetness (Ragone, 2014; Sikarawr et al., 2014; Zerega et al., 2005).

Other plant parts are functional as well. In Hawaiian culture and crafts, the wood of the tree could be used for carving small canoes and surfboards, and the sticky latex sap excreted by a wound was used in bird-catching techniques (McCoy et al., 2010). The dried male flower of the breadfruit can be used as an insect repellent when burned and is reported to be more effective than DEET (diethyltoluamide) (Avant, 2013). Some cultures use the leaves as a food-wrapping for underground ovens or other cooking methods. The leaves have also been found to hold anti-inflammatory, anti-malarial and atherosclerotic properties, as well as cytotoxicity, and improvement in renal function (Baba et al., 2016). Furthermore, the bark was found to be antimicrobial and anti-oxidative. Its heartwood and root cortex even reported to be anti-cancer and offer aspects of UV-protection (Baba et al., 2016).

Local communities around the world have turned their attention to breadfruit for its well-rounded usefulness and other reasons related to human and environment health and agricultural productivity. Across the Pacific and into the global tropics, the fruit tree is often a home-garden crop but also a key component in agroforestry systems (Deivanai and Bhore, 2010; Lincoln and Ladefoged, 2014; Lincoln and Vitousek, 2017; Ragone, 1997). This method generally utilizes a layout of tree crops and smaller shrubs or plants that do well under intermittent shade in the under-canopy; in the case of several Oceanic regions, co-crops included yams, taro, banana, sugar cane, and others. Grown in this fashion, breadfruit aids in soil retention and soil carbon sequestration (Albrecht and Kandji, 2003).

1.3 Thesis Research Objectives

This research intends to add to the growing body of breadfruit knowledge by addressing environmental factors that may influence nutritive aspects of the fruit itself. As previously mentioned, the tree crop is being adopted by farmers across the global tropics, which introduces new growing conditions to consider for management practice. Beyond this, however, a potentially equal in importance inquiry is the interaction between these new, and old, environments and the nutritional composition of the fruit. There are several aspects of this interaction that could be analyzed however only three are investigated through this research: 1) a global review of breadfruit nutritional studies analyzed by study location, 2) an analysis of breadfruit nutritional composition from sources across four Hawaiian Islands, also analyzed by environmental variables, and 3) a consumer survey that addresses the current consumption patterns and behavior of Hawaiʻi residents and breadfruit.

A. *Global Meta-analysis*

To examine the impact of environmental variables on nutritive value of breadfruit, data was mined from an extensive literature review of breadfruit nutritional studies; the data was used to conduct a meta-analysis of breadfruit nutritional data from various locations throughout the global tropics in the context of the climatic and soil environments.

B. *Hawaiʻi Analysis*

Similar to the goals as the previous analysis, new nutritive data was generated for breadfruit in Hawaii. As climates and soils vary heavily across Hawaiian landscapes, Hawaii offers an excellent opportunity to test the impacts of local abiotic factors on nutritional quality of foods. Locally grown breadfruit was analyzed for nutritional composition and examined in the context of of climate and soil parameters to understand their relative impacts for each farm site and fruit samples.

C. *Consumer Survey*

In beginning to discover the relationship between environment and fruit quality, this portion of the thesis research aimed to gain an initial understanding of how breadfruit is interacted with by Hawaii residents and some visiting the islands. The survey addressed areas of consumption patterns, preparation methods and health awareness, as well as carry out general demographic measurements.

Chapter 2

Meta-analysis of Environmental Impact on Breadfruit from the Global Tropics

2.1 Introduction

A genuine interest in the nutritional value of breadfruit has emerged over the last fifty years, initially through investigations of traditional Pacific diets and more recently coupled to growing promotion and cultivation of the crop globally (Deivanai and Bhore, 2010; Jones et al., 2011a; Jones et al., 2011b; Turi et al., 2015). Breadfruit has been hailed as having the potential to transform agriculture in the global tropics, particularly areas of malnutrition and poverty (Jones et al., 2011a, 2011b; Lucas and Ragone, 2012). Although nutritive values fluctuate amongst cultivars and preparation methods, the fruit is generally a good source of carbohydrates and is rich in certain vitamins and minerals while being low in fat and sugars and having a relatively low glycemic index (Jones et al., 2011a, 2011b; Liu et al., 2014; Meilleur et al., 2004; Ragone, 1997, 2016; Turi et al., 2015). Although protein makes up a small proportion of the fruits profile, breadfruit cultivars offer high quality protein made up largely of essential amino acids (Liu et al., 2015; Nochera and Ragone, 2016; Somashekhar et al., 2013). The Ma'afala cultivar, for instance, is noted to have significantly higher levels of essential amino acids than global staples such as potato, rice, wheat, soy, and maize (Liu et al., 2015).

Staple crops make up a large percentage of food calories for people in developing countries- most of which are located in the global tropics (Pokhrel and Soni, 2019; Shiferaw et al., 2011). Over one billion people globally are malnourished either due to insufficient food calories or lack of adequate nutritive value (Jones et al., 2011a). Breadfruit is promoted in these areas as a crop that can aid in agricultural diversification, hunger mitigation, and human nutrition (Turi et al., 2015). Breadfruit is highly productive and can persist and produce in marginal habitats (Lincoln and Ladefoged, 2014; Meilleur et al., 2004; Ragone, 2006; Zerega et al., 2005b). As a long-lived tree it also contributes to environmental benefits such as soil rehabilitation, carbon sequestration, and water and nutrient use efficiency (Abbas et al., 2017; Jose, 2009).

From 2009 to 2017, the Breadfruit Institute of the National Tropical Botanical Garden distributed over 100,000 breadfruit trees to over 40 countries in the global tropics through the Global Hunger Initiative (Lincoln et al., 2018). Combined with historical distributions, this brought the crop into a vast array of growing conditions throughout tropical and subtropical regions, yet no previous studies have looked at the impact of environmental variables on nutritional values of breadfruit.

The potential relationships between climate, soil, and fruit nutritional quality, are important to understand in order to gain further insights into the potential role and impact of breadfruit on human nutrition. This can further support local farmers, breadfruit cultivation, and promote accurate nutritional information for consumers wherever breadfruit is being grown. Furthermore, as climate change is rapidly upon us, shifting temperate and tropical regions present both agricultural limitations (Raiten and Combs, 2019) as well as opportunities to improve food productivity and accessibility through the incorporation of alternative food crops such as breadfruit. Through a review of the existing literature, we utilize previously derived data to examine external environmental factors on fruit nutrition.

2.2 Background

A. Variations in Breadfruit Nutrition

Previous reviews of breadfruit nutrition (e.g., Leakey, 1979; Ragone, 2014; Turi et al., 2015) and extensive studies of varietal impacts on nutrition (e.g., Jones et al., 2011a; Liu et al., 2015) have been carried out. The most recent and extensive literature review covers 41 individually and globally comprised studies (Turi et al., 2015). The compilation included various cultivars and preparation methods, including fresh (raw), boiled, baked, and flour, and examined nutritive aspects such as proximate analysis (energy, carbohydrates, lipids, protein, insoluble and soluble fiber), carotenoids and vitamins, and minerals. Fruit maturity, species and cultivar, and amount of studied cultivars were documented if originally provided.

As Turi et al. (2015) point out, there is some variation in methodology. Proximate analysis is a method of analyzing animal feed and has been the standard protocol in examining food composition, but analytical methods varied, particularly over time, and may compromise a confounding factor when compiling studies. Fiber, for instance, has been altered over time to include some carbohydrates such as resistant starch, hemicelluloses, and pectin (Turi et al., 2015).

Nutritive values are heavily influenced by maturity for all kinds of fruits (Crisosto et al., 2010; Mahmood et al., 2012; SabahelKhier et al., 2010; Sanchis et al., 2015; Villa-Rodriguez et al., 2011). In the case of breadfruit, this important factor is not always indicated by each study and moreover the vernacular used, such as 'immature', 'very ripe', or 'firm,' are not necessarily well defined. To date, a method for standardizing the measurement of fruit maturity for breadfruit has not been developed. This is problematic in nutritional research as important aspects of the fruit, particularly the content of carbohydrates and sugars for breadfruit, is heavily dependent on stage of maturation (Broomes, 2009; Worrell, 1994).

Finally, breadfruit exhibits substantial nutritive variation based on the cultivar (Jones et al., 2011a; Liu et al., 2015). Human domestication of breadfruit species over time has resulted in hundreds of different cultivars that are composed of two species (*A. altilis, A. mariannensis*) and hybrids (*A. altilis* x *A. mariannensis*) (Jones et al., 2013). An issue in compiling previous results is that in general very few studies report cultivar names and when names are reported often times local (rather than standardized) names are used. Furthermore, previous botanical confusion results in occasional misrepresentation of breadnut (*A. camansii*) as breadfruit (Aurore et al., 2014). An extensive study conducted at the world's largest germplasm of breadfruit varieties indicates that it is not possible to accurately identify breadfruit cultivars from morphological features alone, further complicating the accurate reporting of cultivars (Jones et al., 2011a).

B. Environmental Influencers on Fruit Quality

Internal change(s) of a crop (fruiting body) caused by external factors are due to physiological responses to a scarcity or excess of growing requirements (Wang and Frei, 2011). Only a single study (Cao et al., 2006) was identified that examined physiological response patterns and their impact on nutrition for breadfruit. Cao et al. (2006) indicates that breadfruit experiences an increase in antioxidant concentrations when in colder temperatures; this is likely a result of compensating for inadequate photosynthesis.

Research of other crops provide some expectations when examining the role of climate on vegetable, seed, and fruit nutrition. Several studies have attested to crop qualities being affected by abiotic stress, often denoted as having three components: the type(s) of environmental variables, the time and intensity of applied stressors, and species or cultivar susceptibility (Porter and Semenov, 2005; Rouphael et al., 2012; Wang and Frei, 2011). The specific combination of these three components results in the potential tolerance and reaction to abiotic stressors. The word "quality" in "crop quality" or "food quality" in these contexts is generally taken to mean any aspect of the crop, especially those that affect growth and development and ultimately marketability. Plant physiological responses to these external factors are more frequently reported with regard to the impact on overall yield and crop productivity than they are in the context of nutritional qualities as related to human nutrition.

Among the most influential environmental factors that contribute to the quality of crops are light, temperature, and precipitation which are all influenced by climate change (Dinesh and Reddy, 2012). Though they are often studied independently as external factors, soil characteristics are heavily shaped and determined by these climactic variables as well. Individually and collectively, these factors have been known to impact an array of food crops and specific mechanisms such as starch biosynthesis in cereals (Beckles and Thitisaksakul, 2013), lycopene content in tomatoes (Kuti and Konuru, 2005), abscisic acid accumulation in fruit ripening (Leng et al., 2014), chilling injury in carambola fruit (Perez-Tello et al., 2001), impact on potassium function (Cakmak, 2005), and day length impacting papaya and banana glucose levels (Wall, 2006).

All crops require a specific combination of growing conditions to perform optimally, with any deficit or excess in these conditions resulting in suboptimal productivity. Hasanuzzaman et al. (2013) present a helpful visual regarding the effects of temperature on physiological response; the figure shows optimal growth rate, enzyme activity, respiration, and photosynthesis are represented by overlapping bell curves of an optimal temperature. Wang and Frei (2011) demonstrate patterns of nutritional changes in a range of foods based on "abiotic environmental stresses" such as drought, salinity, heat, UV radiation overexposure, and tropospheric ozone. Although only two tree crops were included, kiwi (*Actinidia deliciosa*) and apple (*Malus* spp.), results suggested effects of these abiotic stresses on protein, lipids, non-structural carbohydrates, minerals, antioxidants, and feed value. When growing conditions are not favorable, causing plant stress, there is typically an increase in proteins and antioxidant content, and a decrease in lipid and starch concentrations. As breadfruit is a tropical to sub-tropical crop, we can expect to see unfavorable aspects of productivity among trees that are being grown outside of these latitudes in a natural field setting where temperature and other variables cannot be controlled, and where these conditions lie on the extreme ends of the aforementioned bell-curve.

Other important considerations when weighing environmental factors are timing and intensity. Breadfruit has two known phases of fruit growth: first, size generation, then a major increase in starch accumulation (Worrell et al., 1998). Growers have also observed generally two seasons of breadfruit, the first lasting longer than the second. Worrell et al.'s study suggests that a "resting" period between growth phases could be due to reduced rainfall. After further speculation, though, the plant may be physiologically transitioning between phases. There are no studies that address time and intensity of light, temperature, or precipitation application during one or both growing phases, however we expect that changes in variables will cause the plant to respond differently depending on the current phase of growth. Based on this cumulative information that gives some insight into the relationship between environmental conditions and crop response, this study is conducted based on the hypothesis that fruit nutrient composition will be effected by one or multiple environmental variables that are examined in this study, and that perhaps precipitation, among the other measurements, will prove to be an impactful factor in the variation of at least carbohydrates.

2.3 Materials and Methods

Using combinations of search terms – "*Artocarpus, altilis, mariannensis, communis*, breadfruit, nutrition, nutritive, and proximate analysis" - on multiple search engines (Google Scholar, Web of Science, and CAB Direct), 108 studies in English focused on breadfruit nutrition were retrieved. To these papers we applied several criteria. The studies needed to 1) conduct some sort of nutrition analysis, including proximate analyses, 2) needed to use mature, uncooked breadfruit for analysis, and 3) needed to include the location of the fruit source. After narrowing by criteria, 41 of the retrieved papers were included in the analysis (Table 1).

Data from each study was extracted and converted to common units of analysis; for studies that used multiple varieties for a single location data were averaged in each category (all data is available as Appendix A). For analysis we only included nutritive aspect that had at least eight different studies report comparable figures. Of the 46 categories of nutrients and or nutritive aspects represented by the 41 studies, 27 categories were represented by eight or more studies: proximate analysis components (energy, ash, crude fat, crude protein, crude fiber), starch, total carbohydrates, thiamine, riboflavin, niacin, and several macro- and micro-nutrients (nitrogen (N), phosphorus (P), magnesium (Mg), potassium (K), calcium (Ca), sulfur (S), boron (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and aluminum (Al).

Latitude and longitude coordinates for each study site were used to retrieve environmental data in ArcMap 10.6.1. Global data sets for average monthly temperature, rainfall, solar radiation and vapor pressure were retrieved from WorldClim (http://www.worldclim.org); global elevation was retrieved from the ASTER Global Digital Elevation Model (https://asterweb.jpl.nasa.gov/gdem.asp); global soil pH and cation exchange capacity was retrieved from the International Soil Reference and Information Center (https://www.isric.org/explore/soil-geographic-databases); and categorical representation of soil nutrient availability and retention was derived from Harmonized World Soil Database (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). Average monthly measurements were not taken from a specific year, rather were gathered by the aforementioned databases from a 20-year average.

Extracted climate and soil data were joined to nutritive aspects of the studies. Monthly climate data was averaged or summed depending on the parameter to derive an annual figure. Summary of the site statistics for environmental and soil parameters is provided (Table 2a and 2b). For analysis of monthly climate data, we shifted the Julian-based calendar to fix “Month 1” for each location as the month in which the sun is at its zenith; this has been shown to align well with the onset of flowering in breadfruit (Jones et al., 2010). Nutrition and environmental data were organized and cleaned in Excel 16.23 (Microsoft Corporation, Redmond, WA). Data exploration was conducted in JMP Pro 14.0 (SAS Institute, Cary, NC). and data analysis in RStudio (FOAS & JSS, Boston, MA). Linear regressions were used to assess the significance of relationships between climate and nutrition, and soil and nutrition. Three multivariate regressions were conducted for the nutritive aspects: all environmental variables, all soil variables, and all climate and soil variables together.

2.4 Results and Discussion

A comprehensive table of all relationships described below between nutritional data, soil characteristics, and climate data, is provided (Appendix A). Summary statistics for the nutritive aspects is provided (Table 3). The general nutritive values represented are in line with previous reviews of breadfruit nutrition, which is not surprising since many of the studies utilized overlap (e.g., Turi et al., 2015).

Due to confounding factors discussed in the Introduction of this study, we may suggest implications from significant and insignificant relationships however we are unable to make any statements regarding their causation. An additional confounding factor in this meta-analysis is the inability to report farmer management practices such as use of fertilizer, other soil amendments, irrigation techniques, plant positioning, pruning, mulching and others. Also, we are unsure that the location provided by each study is true to the growing source, as some report that fruits were obtained via a local market, and therefore the extracted environmental data may not perfectly represent the actual cultivation site.

For these reasons, we discuss our findings with the intention of understanding the overarching concepts within systems of growing environmental condition and nutritive quality. Study-specific protocols were not noted in this meta-analysis and nutritional content was extracted and analyzed on the premise that these methods are standard-use across food composition analyses. In an effort to assess the impact of analysis method on the reported figures, we examined the linear relationship between the date of the study and the nutritive parameters. Two important analyses within proximate analysis showed significant relationships, including gross energy ($p>0.017$; $r^2=0.29$) and crude fiber ($p>0.012$; $r^2=0.24$). The trend in crude fiber is consistent with changing methods that have expanded to include aspects of fiber that were previously excluded (resistant starch, pectin, etc.).

All results are expressed within variable to variable correlations (Figures 1 and 2). Correlations between climate and soil characteristics and nutritional values are shown in a matrix (Figure 1), and monthly precipitation impact on nutritional values is displayed across a 12-month timeline (Figure 2).

A. Climate impact on breadfruit nutritional qualities

A1. Proximate Analysis

Overall, categories of nutrition within proximate analyses showed moderate response to environmental variables, with the most significant correlations to proximate components of nutrition driven by precipitation (Figure 1). Precipitation showed significant relationships to ash, energy, protein, fat, starch, carbohydrates, and fiber. These relationships were exclusively negative, so that as rainfall levels increase the nutritional values (or nutrient content) decrease. Solar radiation showed a strong and significant relationship with total carbohydrates ($p>0.0017$; $r^2=0.38$); this relationship was again inversely correlated. Elevation demonstrated significant relationships between total energy ($p>0.0132$; $r^2=0.33$) and total carbohydrates ($p>0.0435$; $r^2=0.18$); these relationships were positive so that at higher elevations higher levels of nutrition are expressed. Temperature and vapor pressure showed no significant impact on proximate aspects.

In general, these findings support the notion that proximate analyses do interact with environmental variables and that increased stress (lower rainfall, low radiation, increased elevation) results in higher levels of nutrition in this category. A multivariate analysis using all climate variables demonstrates moderate to very high r^2 values for most nutritive parameters in this category (Table 4a) with measurements of energy (r^2=0.69), starch (r^2=0.97) and total carbohydrates (r^2=0.72) strongly expressing a reaction to environmental parameters.

A2. Macro- and Micro-nutrients

There were no significant correlations between any of the five climate variables and macro- or micro-nutrient content across sites, except in the case of zinc (Table 4a). Zinc showed highly significant correlations with vapor pressure and temperature. Together with copper, zinc is known to play a role in maintaining a balance of the formation and removal of oxygen. When plants are stressed, there is an imbalance in oxygen levels, with zinc and copper being utilized as the first defense mechanisms concentrated in chloroplasts, cytosols, and other extracellular space (Alscher et al., 2002). If vapor pressure and temperature impact said spaces in which zinc is operating, or increase stress or oxygen imbalance, they may contribute to altering zinc concentrations.

Given that climate does not appear to play a large role in this category of nutrition, it is possible that 1) soils and nutrient availability play a larger role in driving fruit nutrient levels, 2) that the level of variation of micro- and macro-nutrients is not high enough to see trends in their concentrations, or 3) that confounding factors such as variety play a larger role in the variation. As we will demonstrate, soils do not appear to play a significant role in this category, and variation within each type of micro- and macro-nutrient is relatively high. We therefore suggest that other factors such as variety or tree age could be primary drivers to the variation seen.

A3. Vitamins

Vitamin concentrations in fruits show strong correlation with three, sometimes four environmental variables. Thiamine displayed significant correlations with vapor pressure, temperature, and precipitation. Amongst other variables, our results indicate that precipitation also impacts carbohydrate content; this correlation may be related to the fact that thiamine (vitamin B1 complex) is the mechanism which helps the metabolization of carbohydrates (Vicente et al., 2009). Riboflavin was significantly correlated with elevation and temperature, and niacin content correlated with all climate factors except solar radiation. These three vitamins in particular demonstrated very high correlations as reflected in the r^2 values of the linear regressions (Figure 1). A deeper exploration into impact on vitamin concentrations can be found in the following analysis of monthly weather patterns. Though we do not fully understand the reason(s) for the relationships found, we can infer that vitamin concentrations in breadfruit are sensitive to growing conditions. When applying a multivariate regression using climate parameters, the three vitamins demonstrate significant and high r^2 values (0.98, 0.88, and 0.74 for thiamine, riboflavin, and niacin, respectively) (Table 4a).

Overall, we found that precipitation is by far the most influential driver to nutritive aspects, appearing to affect proximate analysis and vitamin concentration. Temperature and elevation, which correlate to each other, also tends to play a role in influencing nutritive aspects of breadfruit.

B. Monthly weather patterns impact on breadfruit nutritional qualities

Fruit ripening, which determines fruit maturity, is a critical process that relies heavily on timing and intensity of specific growing conditions. In an effort to understand how month-to-month weather patterns may play a role in breadfruit nutrition, we utilized average monthly precipitation data to examine patterns throughout the year. For this exercise we only utilized precipitation as the most influential of the climate parameters examined. Rather than use the Julian calendar, we denoted “Month 1” to be the month that the sun was in zenith at each location and also the first day of flower onset—this type of calendar was informed by Jones et al. (2010) exploration of breadfruit seasonality.

Caloric values (energy) and total carbohydrate levels resulted in negative correlations with precipitation throughout the year, but these were much stronger in the last three months of the zenith-based calendar (r^2 values in the last three months averaged 0.68, while averaging 0.25

in the remaining 9 months) (Figure 2). This would be the three months prior to harvest season, encompassing much of the fruit development period. While the patterns were not as clear for other proximate measurements, in general it could be seen that months 6-9 had the weakest (nearest to 0) correlation values for all categories of proximate analysis. Starch in particular was variable throughout the year, with months 2-6 indicating moderate positive correlation and months 6-10 showing strong negative correlations. Sugar content held a positive correlation with precipitation throughout the year, but those correlations weakened in months 4-7.

Macro- and micro-nutrients appeared unaffected by average annual precipitation except in the case of zinc. For every macro- and micronutrients, the strongest correlation value (all negatively correlated) was seen in month 12 (immediately prior to harvest season), while the weakest correlation was in months 5-7 (peak off season). When averaging correlation values across all the micro- and macro- nutrients, moderate correlation (0.3 to 0.6) occured in months 9-12, while very weak correlations (0.02 to 0.09) occured in months 2-6. Manganese, zinc, and copper are known to be fairly immobile micronutrients in the plant phloem and decreasing concentrations through seasons are common for fruits (Storey and Treeby, 2000; Clark et al., 1989). Although there is a threshold to the severity of drought that a plant can withstand before particular plant parts and internal mechanisms begin to break down, there is also reason to believe that moderate drought will increase nutrient concentrations (Fischer et al., 2019). From these findings we cannot give reasons for the timing of the impact of precipitation, however we might infer that because the last months of development are typically for the laying of starch reserves, the accumulation and retention of micronutrients may be happening and or stored in a different location in the plant.

Thiamine, riboflavin and niacin were significantly correlated with monthly precipitation as they were with average annual climate data, with annual patterns apparent. Thiamine was strongly correlated with precipitation for months 1-7 of the growing year (r= 0.86 to 0.99), with moderate to low correlations in the remaining months. Thiamine, or vitamin B1, is a critical component to several metabolic processes that take place in plants and is known to play a protective role from biotic and abiotic stress and are known to be produced in near exact amounts that it is demanded by the plant (no more and no less) (Subki et al., 2018). Riboflavin appears to show the inverse annual pattern to thiamine, with significant negative correlations to precipitation in months 7-12, with very moderate or low correlations in the remainder of the year. No clear pattern throughout the year was apparent with niacin.

Although this study did not look into the mechanisms that may be driving positive or negative correlations between precipitation and nutritive value in the annual patterns, our anecdotal interpretation of the results seems to indicate that for most aspects of breadfruit nutrition there appear to be important patterns that occur throughout the year in regards to the fruiting season, and further investigation of these patterns are likely worth investigating in the future. Such knowledge could inform the manipulation of the patterns to change the nutritive value of the crop, such as apply or denying irrigation to the tree at certain times of the fruiting cycle.

C. Soil characteristics impact on breadfruit nutritional qualities

Soil characteristics are highly determined by climate and also influenced by short term weather. As all of the aforementioned climate variables play a role in defining each of the following soil qualities we have measured, it is difficult to isolate these aspects without assuming that their impact on nutritional qualities of breadfruit are unrelated or not working together with one or more of the climate factors. Unfortunately, global soil data was difficult to retrieve, and quality soil data was only acquired for cation exchange capacity (CEC), pH, water holding capacity, and texture. Composite representations of soil quality were also acquired for nutrient availability, nutrient retention, and toxicity.

C1. Proximate analysis

Cation exchange capacity (CEC) was the most impactful factor to the proximate nutrient values. CEC significantly impacted levels of energy ($p<0.001$, $r^2=0.63$), protein ($p<0.01$, $r^2=0.27$), fat ($p<0.02$, $r^2=0.19$), carbohydrates ($p<0.001$, $r^2=0.67$) and fiber ($p<0.001$, $r^2=0.24$) (Figure 1). CEC is commonly correlated with macro- and micro-nutrient concentrations in the crop due to antagonistic relationships among elemental concentrations in the soil and elemental concentrations in the fruit (Reddy et al., 2014). The availability of nutrients in the tree may be a driver to these categories mentioned here.

Only a few other soil characteristics showed significant correlations to proximate analysis aspects, such as texture and toxicity. Energy levels were influenced by soil texture ($p<0.03$, $r^2=0.28$) and toxicity ($p<0.02$, $r^2=0.29$), as was total carbohydrates ($p<0.04$, $r^2=0.21$; $p<0.02$,

r^2=0.23). As previously alluded, soil texture is a characteristic that determines a number of important plant interactions, such as nutrient retention and capacity, soil moisture, and drainage. Toxicity can both directly affect the plant through damaging or inhibiting plant functions, but can also play a role in binding or competing with similar nutrients in the soil.

Fiber content displayed significant correlations with nutrient retention, nutrient availability and soil toxicity. Fiber components in plants are normally concentrated in stems and branches of fruits and vegetable crops where cell walls can be made of large proportions of fibrous parts such as lignin, resistant starch, and some carbohydrates. Although the breakdown of fiber components is not entirely clear in the case of breadfruit, it is known that at least cellulose, which can represent upwards of 33% of the cell wall, does not change with ripening (Vicente et al., 2009). This could suggest that perhaps no matter the maturity of the fruit, fiber levels will consistently be impacted by soil variables. A multivariate analysis of all soil variables with nutritional components also shows more substantial significance and correlations (Table 4b).

C2. Macro- and micro-nutrients

Similar to our climate results, macro- and micro-nutrients do not appear to be significantly impacted by any of the measured soil characteristics (Figure 1). Phosphorus, magnesium and zinc were the only nutrients that held significant relationships with one or more soil characteristics. Phosphorus ($p<0.04$, r^2=0.24) and zinc ($p<0.02$, $r^{2=}$0.61) showed impactful correlations to CEC, and magnesium to water capacity ($p<0.04$, r^2=0.35).

C3. Vitamins

Riboflavin did not reveal any significant impact from soil characteristics (Figure 1). Thiamine was significantly correlated to soil texture ($p<0.04$, r^2=0.55), and both thiamine and niacin showed impactful relationships with nutrient availability ($p<0.001$, r^2=0.71; $p<0.01$, r^2=0.61), retention ($p<0.001$, r^2=0.94; $p<0.00$, r^2=0.66), and soil toxicity ($p<0.02$, r^2=0.75; $p<0.01$, r^2=0.60). Based on these findings, it seems that although there are few strong correlations to particular soil characteristics, vitamin concentrations are more influenced by when considering climate factors. A multivariate model using all soil parameters showed fairly high r^2 values (0.97, 0.64, 0.89 for thiamine, riboflavin, and niacin respectively) (Table 4b).

D. Multivariate analysis & influential factors

A multivariate analysis was done using the primary climate (temperature, rainfall, and elevation) and soil (CEC, nutrient availability and nutrient retention) data as a first order effort to understand their relative importance on breadfruit nutritional value (Table 4c). Relationships from the multivariate model more or less mirror those which have already been discussed in the previous section, in that aspects of proximate nutrients were impacted by CEC, precipitation, and other factors. Vitamins (riboflavin, thiamine and niacin) showed very high correlations to several of our climate and soil measurements, and macro- and micro-nutrients did not show much relationship to majority of these abiotic variables. Discussed below are the results of the multivariate analysis that either add to or change the generally observed patterns of environmental effect on nutritional composition.

D1. Proximate analysis

When analyzed together with soil characteristics, proximate analysis measurements were primarily impacted by climate (precipitation, temperature and elevation) conditions, with CEC playing a lesser role in protein, starch, fiber, and carbohydrate levels. In general, r^2 values were not much improved when using climate and soil variables as opposed to just climate variable.

D2. Macro- and Micro-nutrients

As with previous analyses, minimal predictive power existed for micro- and macro-nutrients. The multivariate analysis using all soil and climate data displayed some significant relationships for phosphorus ($p=0.046$, $r^2=0.34$), iron ($p=0.028$, $r^2=0.42$) and zinc ($p=0.012$, $r^2=0.97$), which were driven slightly more by soil parameters than climate.

D3. Vitamins

Thiamine, niacin, and riboflavin content were significantly impacted by multiple variables in both the soil and climate categories. The mixed model displayed very high r^2 values (0.997, 0.924, and 0.939 for thiamine, riboflavin, and niacin respectively). Thiamine showed high correlation to nutrient availability and retention, and temperature ($p<0.0001$, r^2 0.9971). Riboflavin was correlated with nutrient availability, elevation and precipitation ($p<0.0009$, r^2 0.9242), and niacin showed a significant relationship with CEC, nutrient availability, elevation and temperature ($p<0.0108$, r^2 0.9388).

2.5 Conclusion

As breadfruit continues to expand into the global tropics as a productive and nutritious food crop, it is important to understand how it will perform in various environments, particularly against the limitations of its natural environment. We attempted to address the knowledge gap that is nutrient content variability as it may vary across climate and soil characteristics that are unique to place. As climate change further alters environmental conditions, especially rainfall patterns and intensities (Rojas et al., 2019), growers of the global tropics will need to adapt by determining which crops are best to cultivate and with which management practices. It is important for this field to be further investigated, as many farming communities in poor regions have been and will continue to rely on rain-fed, low-tech, and microclimate-dependent agriculture.

In the midst of few confounding factors, such as inconsistency in reporting cultivars and unknown farmer management practices, we have investigated the impact of growing conditions on the nutritional quality of breadfruit. Environmental data was extracted from studies sites of forty-one experiments that report nutritional content of the fruit; both nutritional and environmental datasets were then examined by a multivariate analysis and the relationships between each were organized into a correlation matrix.

From this meta-analysis we observe few environmental variables that play a role in nutritional content as growing conditions change and vary where breadfruit is being cultivated. Results from climate analysis demonstrated that several parameters were influential, but that rainfall was a dominant driver to many aspects. Results based on the measured soil characteristics showed that CEC is one of the main drivers of proximate aspects of breadfruit nutrition. Other soil factors play significant yet smaller roles in impacting nutritional qualities, and again we find that there are few very strong relationships between environmental factors and vitamin concentrations. Interestingly, no relationship with pH, typically a major soil parameter for the interaction with crops, was seen to any nutritive aspects of breadfruit.

Precipitation and CEC drive several aspects of breadfruit nutritional quality, while other environmental variables more specifically influence other nutritive aspects. In the constant conversation of climate change, a warming planet will cause some places to receive more rainfall than others (Rojas, 2019). Research in breadfruit physiological responses to precipitation, among other climatic variables and alongside the interactions between breadfruit and CEC in soils, should perhaps be a priority in the field of tropical agriculture. For both soil and climate relationships with nutritional composition of breadfruit, we have seen a general pattern of significant relationships between these abiotic factors and proximate measurements as well as vitamin concentrations. Furthermore, we see little to no significant relationship between environmental factors and macro-micro-nutrients (Figure 4a and 4b).

Several improvements can be made to this research in the future by investigating how combinations of these environmental variables, as well as timing and intensity of each, are effecting breadfruit nutrition. Furthermore, as climate change begins to drastically impact these tropical places it would be beneficial to gain an understanding of how growing conditions are projected to change over time and the implications for farmers who are growing breadfruit.

Chapter 3

Analysis of Environmental Impact on Nutritional Composition of Hawai‘i-grown Breadfruit

3.1 Introduction

As breadfruit (*Artocarpus altilis*) gains momentum in the cultivation strategies of communities across the global tropics the interaction between environment and food nutrition in general is important to understand. These interactions are enhanced in the face of climate change, which will affect some parts of the world more severely than others. In order to examine these potential relationships for breadfruit grown in Hawaiʻi, the following study was carried out with the participation of 48 farmers across four of the Hawaiian Islands. The objective of this study was to evaluate the response of fruit nutrient content to variables of microclimate that encompass farming sites across four of the Hawaiian Islands .

A. Disparity in the Pacific: Hawaiʻi's People and Landscape

The highly productive breadfruit has been a staple food in the Pacific for over a millennium (Lincoln et al., 2018). The crop has made its way far into the West since its origins in south-east Asia; today it can be seen cultivated throughout the global tropics. Breadfruit, called ʻulu in the Hawaiian language, has been a contributing crop to the diet of Hawaiian people for centuries prior to and somewhat following the dispossession of land by foreigners. Although kalo, or taro (*Colocasia esculenta*) was the main staple food, native people associated breadfruit with prosperity and abundance, and cultivated it on a large scale as an agroforestry crop in certain regions of the islands (Lincoln and Ladefoged, 2014).

The nearest land mass to Hawaiʻi is 2,000 miles away; with a population topping out at 1.43 million people (Hawaii Population, 2019), and the constant competition for land, the islands have relied heavily on imported food and goods. However, together with the disposession of indigenous lands, a reliance on imported foods has led native and local people combined to dramatically shift from once highly nutritious to heavily processed and empty calorie diets. Not only has this driven the onset of lifestyle diseases such as diabetes and obesity, but it has also disconnected people with traditional foods and practices.

The introduction of imported foods has caused issues for other Pacific Island nations as well, not just Hawaiʻi. Diabetes, heart disease, and obesity are often the outcomes for native people after traditional foods are neglected, and are the topics of interest which breadfruit is believed to positively address (Look et al., 2013; Turi et al., 2015). Among these disparities, tropical and sub-tropical areas account for several, if not the majority, of developing countries that suffer from malnutrition and poverty (Muller and Krawinkel, 2005). There is a continuous need to implement nutrient-dense foods and food solutions in these areas. The steady increase in neglect of traditional foods in Hawaiʻi is one that several people and community groups have been addressing over the past fifty years as the issue of declining health has taken precedence throughout the state. The University of Hawaiʻi's Department of Native Hawaiian Health stated in 2013:

"In general, Hawaiians and Pacific Islanders (NHPI) bear a disproportionately higher prevalence of many chronic medical conditions, such as obesity, diabetes, and cardiovascular disease, collectively known as cardiometabolic disorders…Hawaiians not only have higher rates of death for diabetes and heart disease but also for cancer and other leading causes of death as compared to the overall State's population." (Look et al., 2013)

A recent survey concerning the breadfruit consumption patterns of Hawaii residents showed that Pacific Islanders eat more breadfruit annually than other ethnicities, however native Hawaiians in particular did not eat more than any other ethnic group (see Chapter 4). In fact, no ethnic group aside from non-Hawaiian Pacific Islanders ate significantly more than another. Thus, the potential benefits of breadfruit consumption would not only have positive impact on the native Hawaiian population, but other communities as well.

Just as diet has changed drastically over the last one hundred years for Hawaiʻi, landscape has followed suit. Former sugar and pineapple plantations, which were once traditionally cultivated or utilized spaces by native people, today have more or less phased out and agricultural lands have shifted commercially (Statewide Agricultural Land Use Baseline, 2015, hdoa.hawaii.gov/salub/). Furthermore, amidst other changes, large bio-tech companies have had the time and money to settle in, continuing mainly monocrop systems like corn seed cultivation (Perroy et al., 2016).

B. Multifaceted Benefits of Breadfruit

Breadfruit is a good source of carbohydrates and fiber. It is also known to have higher quality protein compared to other global staple foods such as corn, soy and wheat (Liu et al., 2015). Though it has an overall low protein value, the small amount that it does is made of essential amino acids such as phenylalanine, leucine, isoleucine, and valine, which are needed in the human body (Liu et al., 2015). It also has a good amount of resistant starch and a low glycemic index, both of which suggest its potential in diabetes control (Turi et al., 2015).

Breadfruit is also a good source of vitamins C, riboflavin, niacin and thiamine, and some minerals such as potassium, phosphorus and magnesium. Breadfruit is hypoglycemic - via glucose absorption and an enzyme that inhibits carbohydrate metabolism, it acts as a counter to diabetes (Baba et al., 2016). A classic Hawaiian example of breadfruit thriving in its growing environment could once be found along the south-westerly mid-land region of Hawaiʻi Island. South Kona boasted the *kaluʻulu* or breadfruit groves that were wide across the landscape and stretched for miles northward, cultivated intentionally where sufficient rainfall for *taro* (*Colocasia esculenta*), the otherwise classic staple for the Hawaiian Islands, tends to drop off (Lincoln and Ladefoged, 2014). In true agroforestry fashion, where intercropping provides a diverse and dense food system, breadfruit was the keystone crop in the *kaluʻulu* and thus offered the environmental benefits that we know agroforestry to do still today such as preventing soil erosion, supporting ecological relationships between plants and animals, increasing crop diversity and indirectly reducing farmer complete reliance on seasonality, providing insurance for arid and semi-arid regions from abnormal weather, and sequestering soil carbon (Abbas et al., 2017; Swaminathan, 1987).

C. Environmental Effect on Nutrition

Previously, a meta-analysis was conducted to examine the effects of climates and soil on nutritional qualities of breadfruit (see Chapter 2). Results were grouped in categories of proximate analysis (ash, moisture, energy, protein, fiber and fat), macro- and micro-nutrients (Ca, K, P, Mg, Na, Fe and Zn) and vitamins (thiamine, ribloflavin and niacin). Within each category, annual averages of climate and soil characteristics, were discussed in reference to how nutritive aspect was influence by each. Overall, measurements of proximate analysis, such as fiber, fat and protein, together with carbohydrates, were impacted most significantly by precipitation, temperature and soil cation exchange capacity. Macro- and micro-nutrients were more or less uneffected by climate or soil characteristics. Vitamins were significantly influenced by multiple climate and soil variables.

Precipitation was the most active player in impacting most nutritive aspects of the fruit, and thus monthly rainfall measurements were examined with nutritive qualities separately. The precursor to this particular perspective is the work of Worrel et al. (1998) which found that breadfruit is known to have two main growing phases: size generation then accumulation of starch reserves. It was curious, then, to look closer at month-to-month weather patterns (precipitation) throughout one year, and fruit nutritional values. Following a zenith-based calendar originally crafted by Jones et al. (2010) that indicated breadfruit flowering as it occurs throughout the global tropics, the seasonal effects of rainfall were investigated.

Based on the global analysis of breadfruit nutrition and environmental variables and suggested outcomes from the literature, we understood that precipitation plays a large part in the fluctuation of some measurements of proximate analysis as well as the concentrations of some vitamins. This data was however globally comprised; the expectations were more or less unknown for this study, which takes a closer look at environment of the Hawaiian Islands.

3.2 Materials and Methods

Fruit and soil samples were collected from 48 participating farms across four Hawaiian Islands: Kauaʻi, Oʻahu, Maui, and Hawaiʻi. Some farms were considered to have multiple "treatments" if planting varied significantly, such as different management (e.g., fertilized vs. non-fertilized), landscapes (e.g., heavily sloped vs. flat), or trees (e.g., multiple varieties). Three mature fruit were gathered per treatment, each from a different tree. One composite soil sample composed of three separate cores was taken from around each tree at a distance from the trunk of ~2m.

All samples were taken to the University of Hawaiʻi at Mānoa and processed in Laboratory. Fruit were washed and wiped with paper towels and photographed. Each fresh sample was then separated into sub-samples: peeled and cored, and not peeled/not cored. Subsamples were chopped then put into a food processor. The end results were dried in an oven at 60 ℃ for 72 hours then ground into a flour-consistency.

Portions of the fruit samples were sent to the University of Missouri-Columbia Agricultural Experiment Station Chemical Laboratory to undergo proximate analysis. This included the measurements of ash (AOAC Official Method 942.05, 2006), moisture (AOAC Official Method 934.01, 2006, vacuum oven.), crude fat (Acid Hydrolysis, baked goods & pet food, AOAC Official Method 954.02, 2006.), crude fiber (AOCS Approved Procedure Ba 6a-05; AOAC Official Method 978.10, 2006), and crude protein (Kjeldahl, AOAC Official Method 984.13 (A-D), 2006).

Soil samples were sent to Brookside Laboratories (New Bremen, Ohio) for analysis of pH, organic matter, estimated nitrogen release, Bray I phosphorus, exchange capacity, percent base saturation of cation, available nitrogen (NO_3-N + NH_4-N), and Mehlich III Extractable P, Mn, Zn, B, Cu, Fe, Al, S, Ca Mg, K, and Na.

To further the amount of nutritional data we derived from the UMC Agricultural Experiment Station Lab, the following analyses were carried out at the University of Hawaiʻi at Mānoa Agricultural Science Building in the laboratory and under the direction of Dr. Rajesh Jha of the Department of Food Science and Human Nutrition in the College of Tropical Agriculture and Human Resources. Gross energy (GE) content was determined using an oxygen bomb calorimeter (Parr Isoperibol Bomb Calorimeter 6200; Parr Instrument Co., Moline, IL, USA) with benzoic acid as the calibration standard. Weighed pellets were placed into a crucible and energy measured by heat given off of sample and resulting change in temperature of surrounding water.

Both total starch and resistant starch analyses were conducted for samples of the Ma'afala cultivar only; this was to control for variation when examining the effects of environment on nutritive values. Total starch determination was carried out using a Megazyme Assay Kit (Amyloglucosidase/alpha-amylase method; AOAC Method 996.11, AACC Method 76.13, ICC Standard Method No. 168). After initial protocol procedures, the samples were treated with a glucose-releasing reagent (GOPOD reagent), incubated, then read at 510nm in a spectrophotometer (Evolution 201, Thermo Scientific, Waltham, MA). Resistant starch analysis was carried out using a Megazyme Assay Kit (AOAC Method 2002.02, AACC Method 32-40). After initial protocol procedures, the samples were treated with a glucose-releasing reagent (GOPOD reagent), incubated, and read at 510nm in a spectrophotometer (Evolution 201, Thermo Scientific, Waltham, MA). The resulting values were calculated using the equation below and a starch percentage on a dry-weight basis was derived using reported sample moisture:

(g/100g sample; for samples containing >10% RS):

$$= \Delta E \times F \times 100/0.1 \times 1/1000 \times 100/W \times 162/180$$

$$= \Delta E \times F/W \times 90$$

Soil samples were collected and stored in a refrigerator over a duration of three to four days. They were then wet-sieved and subsampled. Wet subsamples were used for soil moisture determination, pH, and nitrate and ammonium via KCl extraction. Additional subsamples were dried at 60 ℃ for 72 hours and ground to a fine powder with a mortar and pistol. Organic carbon was estimated using loss on ignition methods at 375 ℃ for 24 hours. Soil samples were sent to Brookside Laboratories (New Bremen, Ohio) to undergo analyses for extractable nutrients (Mehlich 3) and total exchange capacity.

Climate data was extracted for each farm site using the Hawai‘i Rainfall (Giambelucca et al., 2013) and Evapotranspiration Atlases (Giambelucca et al., 2014). Climate measurements included annual averages of precipitation, temperature, solar radiation and elevation. Rainfall average measurements were gathered from the years 1874 to 2007 and reported in 2011 (Giambelucca et al., 2013). Evapotranspiration data was averaged from measurements over the past ten to twenty years (Giambelucca et al., 2014).

All data was cleaned in Excel 16.23 (Microsoft Corporation, Redmond, WA) and analyzed in RStudio (FOAS & JSS, Boston, MA) and JMP Pro 14.0 (SAS Institute, Cary, NC). Three multivariate models were created to look at parameters separately and together. The first examined climate variables, the second soil variables, and the last both set of variables combined. We first created correlation matrixes for all environmental parameters and soil parameters separately. We removed variables when high (<0.9) cross-correlations occurred. A generalized linear model using standard least squares was conducted using a forward selection method; we stopped introduction of parameters when the effect level of the new variable was insignificant ($P > 0.05$).

3.3 Results

Summary statistics for study site environmental measurements are in Table 5 and nutritional composition of all samples organized by cultivar can be seen in Appendix B. In general, samples collectively averaged 4.85% fiber (w/w), 4.82% protein (w/w), 18.61 MJ/kg energy, and 1.02% fat (w/w). Macro- and micro-nutrient levels were fairly low, with the exception of potassium (1.47%). Samples were made up of seven different cultivars; nutritional compositions can be seen separately across cultivar type in Appendix B. As seen in the appendix, total starch and resistant starch measurements are reported for only the ‘Ma‘afala’ cultivar in order to control for cultivar variation. Resistant starch is a form of carbohydrates that bypasses the small intestine for digestion, remaining in the system for a longer period of time. ‘Ma‘afala’ averaged 47.47% starch and 41.12% resistant starch. Interactions between environmental variables and nutritional qualities are examined in more depth below.

A. Effect of Abiotic Environment on Nutritional Composition

The 48 sampled sites were significantly different from each other in climate variables and soil characteristics. Average annual measurements for climate are summarized in Table 5 and for soil in Table 6.

A1. Proximate analysis

Moisture, fat and fiber were significantly affected by climatic variables while total starch values were slightly significant as well (Table 7). Soil characteristics, however, were more impactful to several aspects of proximate measurements than climate, and overall held higher r^2 values as well. Although this may suggest that soil properties across the sampled sites may play a larger role in nutritional variation for breadfruit than abiotic factors of the growing environment such as rainfall, solar radiation and evapotranspiration, there is the exception for fiber. There were stronger relationships between fiber content and climate factors compared to soil properties and furthermore to a combination of both. Interestingly though, when both climate and soil characteristics are combined in a multivariate analysis, the effect was significant correlations with energy ($p=0.0001$, $r^2=0.49$), protein ($p=0.001$, $r^2=0.35$), moisture ($p=0.0001$, $r^2=0.40$), fat ($p=0.0001$, $r^2=0.45$), fiber ($p=0.001$, $r^2=0.40$), and starch ($p=0.05$, $r^2=0.39$) (Table 7).

A2. Macro- & Micro-nutrients

Aside from magnesium ($p<0.002$), calcium ($p<0.007$), boron ($p<0.05$), zinc ($p<0.05$) and aluminum ($p<0.004$), all other macro- and micronutrients were not significantly affected by climate variables. Soil characteristics seem to be more influential in nutritional levels than climate alone. Furthermore, the combination of the climate and soil variables resulted in greater and more frequent significance across all of the measured macro- and micro-nutrients, just as displayed with the interactions between environmental variables and proximate measurements. The multivariate analysis, conducted for both macro-micro-nutrients and proximate measurements in order to examine the potential effect(s) of combining soil and climate variables, can also be seen in Table 7 in the “Mixed” category.

Literature addressing environmental impact on nutritional composition of crops suggest that the further away the environmental conditions moves from normal conditions for a crop, the more a response, or multiple, can be detected in nutrient composition (Wang and Frei, 2011). Though the Hawaiian Islands have wet and dry seasons, the two are not normally expressed in extremity like how another region in the global tropics may experience regular typhoons or droughts. This consistency in weather, and potentially consistent soil profiles that are specific to each microclimate, could be the reason why several of the nutritional aspects measured for these Hawaiʻi-grown breadfruit are more impacted by multiple abiotic variables than by individual ones.

Considering there were other factors encompassing the study that could be contributing to our results, we decided to report them below. This included samples that were peeled and not peeled and samples of different breadfruit cultivars.

B. *Effect of Peeled vs. Not Peeled*

As previously mentioned in the Materials and Methods section of this chapter, all samples were subsampled into peeled (skin and core removed) and not-peeled (skin and core left intact). For most tropical fruits the skin of the fruiting body, as well as the seed, generally holds a substantial amount of certain nutrients, especially vitamins, compared to the flesh (Vincent et al., 2009). Based on these findings, we hypothesized that whether or not the skin and core was left would have significant impact on some if not all of the nutritional composition of the sample. Indeed, for majority of our macro and micro nutrients, there were higher levels of concentration from samples that had their peel and core left in-tact when processing (Figure 3).

D. *Effect of Cultivar*

Seven cultivars were analyzed in this study, inclusive of an "Unknown" category (see Appendix B). Due to the variability in obtaining breadfruit samples, starch analyses (total starch and resistant starch) were carried out for the Ma'afala cultivar only, which represented 38.9% of all samples. Other cultivars were represented by as low as two samples, and 22 samples were of unknown cultivars. The Fiti cultivar displayed the highest caloric value (energy) compared to all others at an average of 19.63 MJ/kg (n=2). This cultivar was also the highest in protein (7.80 w/w%), fiber (10.60 w/w%) and fat (2.34 w/w%).

With this data alone it is difficult to draw solid conclusions about the role of cultivar in nutritional composition of these Hawaiʻi-grown breadfruit, however other studies (Wootton and

Tumalii, 1984; Jones et al., 2011a) have explored this aspect of nutrition more thoroughly. Comparing just Samoan cultivars, there are reported differences in protein, carbohydrates, fat and fiber, when fruit were mature (Wootton and Tumalii, 1984; Ragone, 2014). It would not be surprising, then, if the Fiti cultivar and others truly displayed their higher values in the corresponding nutritional categories, which again could be investigated for Hawaiʻi breadfruit in a future study with more representatives per cultivar.

3.4 Discussion

Overall nutrition

Nutritional compositions of our breadfruit samples are highly comparable to that of previous nutritional studies (Appiah et al., 2016; Jones et al., 2010; Turi et al., 2015). One quarter of a breadfruit, after loss of skin and core mass (commonly removed when processed or eaten) is roughly 71 g of dry weight (see Chapter 4). If utilizing this average serving size for one person during one meal in Hawaiʻi, together with the nutritional composition of our samples, this serving can offer up to 28.5% of the Daily Recommended Intake (DRI) for fiber for males and 51.7% for females (USDA National Agricultural Library, DRI Tables and Application Reports, https://www.nal.usda.gov/fnic/dri-tables-and-application-reports). Hawaiʻi-grown breadfruit eaten in this portion can also offer 2.5% of the DRI for fat and 21.4% of the DRI for protein. If consuming the variety ʻMaʻafala' in the same serving size, this amount of breadfruit can offer 46.2% of the DRI for starch. Although these are crude calculations, one quarter of a breadfruit from our samples, and likely from others as well, offers a substantial amount of the key nutrients for human nutrition. Furthermore, in addressing the diabetes epidemic not only present in Hawaiʻi but several other tropical regions of the world, the resistant starch values determined for our Maʻafala cultivars is impressive and highly relevant.

Impact of variety

As with previous studies, we saw highly significant differences in nutritive values based on cultivar (see Appendix B) (Jones et al., 2011; Wootton and Tumalii, 1984). Although we were unable to acquire a consistent amount of each reported cultivar, there are few clear distinctions between specific ones. ʻFiti' and ʻOtea' varieties, for example, held higher values than the other cultivars in nearly every nutritional category, such as protein, fiber, energy and fat. Due to the inconsistency in cultivars being grown by farmers, some varieties were more represented than others (Hawaiian Ulu (n=15), Maʻafala (n=30), Fiti (n=2), Otea (n=2), Puou (n=4), Tahitian (n=2)). Consistency in future studies that analyze environment and nutritional composition would benefit from obtaining samples of the same cultivar or at least multiple that are equally represented.

Whole fruit analysis

Within sample preparation approximately half of the samples were peeled and cored to simulate contemporary processing occurring within the marketplace (NWC, Hawaii Ulu Producer Co-Op). However, the skin and core are edible and based on the compositional analysis of other foods, may contain higher nutritive value when consumed together with the flesh. Subsamples that included their skin and core displayed significantly higher macro- and micro-nutrient values than those that were peeled and cored (Figure 3). Although some people will eat the skin of the breadfruit with the flesh, it is more uncommon especially in restaurants and the small commercial spaces which utilize the fruit. This may be a precursor to further research that may encourage consumers to eat the skin for enhanced health benefits, at least in terms of increased macro and micro nutrient availability.

Impact of Environment

Crop nutrition in general is widely studied, especially for globally important crops such as maize and wheat. The overall expected trends are related to abiotic stressors that cause physiological changes in the plant and thus, commonly, altering of the composition of fruiting bodies. Certain nutritional qualities are known to increase when specific environmental aspects of the growing conditions are in excess or in deficit (Wang and Frei, 2011). For instance, protein levels commonly increase during water stress or drought while vitamin concentrations may also increase for more tropical plants when it experiences colder temperatures (Wang and Frei, 2011). For these known trends, we understand why protein in particular was seen to have a significant relationship with monthly precipitation for most of the months out of the year (see Chapter 2).

Our results in this study more or less mirror that of Chapter 2, which also analyzed the interactions between environmental variables and nutritional composition of breadfruit. We see that among proximate measurements, there are nutritive aspects that are effected by both climate and soil. Conversely, macro- and micronutrients have showed little to no significant interactions with climate nor soil. From a global perspective, and with certain variables left unknown such as cultivar type and maturity often unreported from utilized studies, we now know that precipitation and soil CEC displayed the most effect on nutritive qualities of breadfruit. Macro- and micronutrients, also telling in this Hawaii-based study, though not significantly impacted by these environmental factors, could be interacting with different environment or plant physiological mechanisms than those we have examined; this could include age of trees, use of pruning, or forms of soil amendment.

Seeing that climate and soil variables were more impactful to nutritional qualities together than alone could be due to a number of different reasons. First, a couple of confounding factors have led to further research questions that can be addressed in future studies. Treatments, for example were not the same across each farm. In future studies, it may be beneficial to examine fruits separately by cultivar then by farmer management practice. Another good method would be to replicate the study across an appropriate time span while collecting additional data for the trees, such as leaf tissue samples, that may provide a foundation for overall tree health. The predicament this would have presented for the current study is the amount of trees available for sampling after controlling for variation. Despite this, through events such as the now annual breadfruit festival (Lā ʻUlu) and a recent tree giveaway (over 10,000 breadfruit trees dispersed locally), the number of trees growing on Hawaiian Islands will increase and in time could possibly accommodate a study with said parameters.

3.5 Conclusion

As breadfruit moves deeper into the crevices of the world, even reaching communities that currently suffer from poverty, malnutrition and food-insecurity, its nutrition in full-spectrum becomes more and more valuable, relevant and impactful for human health (Muller and Krawinkel, 2005). Especially in the case of the Hawaiian people, who, among other Pacific Islanders and local residents, fall into categories of heart disease, high blood pressure, diabetes and obesity, breadfruit is a highly viable component for good health (Kaholokula et al., 2018). The Hawaiian Islands provide a unique opportunity to unveil interactions between environment and nutritional qualities of crops. Though the results of this study suggest that combinations rather than isolated variables have greater effect on fruit nutritional composition, we also can conclude that research for breadfruit in the areas of farmer management practice could be an important next step in determining nutritional fluctuations across different landscapes.

As climate change may have a drastic and lasting effect on the Hawaiian Islands, some of which we have already seen with sea-level rise, agriculture will need to be diversified and adaptive measures strongly put into practice in order to deliver a substantial amount of healthy food to the island's population. Measurements of and factors influencing healthy food, then, are imperative to understanding how best to deal with environmental change while also addressing current issues surrounding human health. Breadfruit has certainly become a focal point for farmers, consumers, restaurant owners, and others, with the understanding and hope that this crop can aid the efforts to reduce health issues and increase the wealth of the land. Future research could include an in-depth look at farmer management practices for breadfruit and cultivar types as well.

Chapter 4

Consumer Survey

4.1 Introduction

Breadfruit (*Artocarpus altilis*) is a food crop that has great implications for improving food security, supplementing staple foods, and mitigating hunger on a global scale, especially in tropical and sub-tropical regions (Lucas and Ragone, 2012; Turi et al., 2015). Despite these favorable attributes, the fruit is among the top 35 neglected and underutilized crops identified as important to food security (FAO, 2009; Jones et al., 2011) and listed as a priority crop by the Global Crop Diversity Trust (http://www.croptrust.org/ main/lprioritycrops.php). As part of the efforts to increase breadfruit cultivation on an international scale, breadfruit trees have been distributed to 45 countries around the world (Lincoln et al., 2018).

In Hawaiʻi, breadfruit, or ʻulu in the native language, is both agriculturally and culturally important in the history of the Hawaiian Islands (Meilleur et al., 2004). Traditional Hawaiian landscapes included extensive breadfruit agro-forests that produced high yields across broad environmental habitats, with minimal growing requirements. Breadfruit was cultivated as an agroforestry crop, in home gardens, and part of mixed agricultural systems (Langston and Lincoln, 2018), and played a significant role in the agricultural economy of the islands (Lincoln and Ladefoged, 2014). Due to urbanization of landscapes over time, shifting demographics, and a general transition to processed foods, traditional food systems throughout the island chain have largely been lost. However backyard trees, small-scale production, and "wild" trees still remain. In addition, significant efforts have been made to revitalize breadfruit in both Hawaiian landscapes and food systems resulting in an increase of trees at both the household and farm level (Ragone et al., 2016).

Multiple efforts have driven this increase in breadfruit trees, including large-scale tree giveaways (Lysak, 2018) and a growing local food producing sector (Langston and Lincoln, 2018). Consumer education, printed materials and festivals have also contributed to breadfruit's momentum in the islands (Ragone et al., 2016). Such shifts in food production are supported in rhetoric, if not action, by Hawaiʻi's state initiative to double local food production by 2020. The need for this huge increase is seen in the State's most recent statistics on imported foods, which states that replacing a mere 10% of imported food with local production could keep about $313 million dollars within the state (Office of Planning DBEDT, 2012).

Breadfruit could certainly become a valuable crop that can address food security in the Hawaiian islands. Initiatives have already been taken within the past quarter century to bring breadfruit back into production at small, private farm scales, as we see the crop's integration in pre-existing operations growing exponentially (Langston and Lincoln, 2018). Today it is important to better understand the motives of breadfruit consumers and their behaviors, in order to support local farmers and keep the crop relevant in the conversations of agricultural productivity, food security and human nutrition.

In the last forty years, breadfruit has seen an increase in studies globally in tropical and sub-tropical areas (Lincoln et al., 2018). Despite this increase, a recent review paper indicates that "breadfruit remains a vastly understudied crop, and could benefit from a wide range of basic investigations" (Lincoln et al., 2018, pg. 363). The fruit crop has received relatively good attention within the realm of nutrition and is widely promoted as a nutritious starch alternative. The light-colored flesh provides a substantial amount of carbohydrates, fiber, and macronutrients such as potassium, calcium, and magnesium. Breadfruit is also a good source of B and C vitamins, however these and other nutritive aspects are influenced by cultivar and fruit maturity (Jones et al., 2011; Turi et al., 2015)

The fruit is generally not rich in fats or protein, but does consist of high quality proteins necessary for human nutrition (Liu et al., 2015, Nochera and Ragone, 2016). The Ma'afala cultivar in particular is noted to have a significantly greater total amount of essential amino acids than other cultivars and of higher quality than other globally recognized staples like corn, peas, soybean, rice, and potato (Liu et al., 2015). For these reasons, breadfruit is especially studied to mitigate hunger in rural areas that may live in poverty (Lucas and Ragone, 2012). Furthermore, the fruit's low glycemic index and high fiber content may combat lifestyle diseases such as diabetes: a prevelant issue amongst Pacific Islander populations (Turi et al., 2015).

While breadfruit has been examined from ethnographic, agronomic, and post-processing perspectives, consumption of breadfruit has been scarcely investigated. Only a single study that addresses breadfruit consumption was identified in Trinidad, West Indies (Roberts-Nkrumah and Badrie, 2005), and a separate study in Hawaiʻi examined consumer willingness to pay for breadfruit products (Lysak, 2018). The objective of the current study is to address consumption patterns and characteristics of Hawaiʻi residents in order to better understand factors that may drive or inhibit consumption.

4.2 Methods

A 10-question survey was created to investigate frequency of consumption, source(s) of breadfruit, method(s) of preparation, awareness of health benefits, and consumer demographics (full survey available as Supplemental Table). On average, a respondent spent two to three minutes to complete a survey. Questions were multiple choice with additional comment boxes for encouraged open-ended responses. The survey was piloted with a student population at the University of Hawaiʻi at Manoa and refined for clarity and accuracy. The survey was made with SurveyMonkey Inc.™ (San Mateo, CA) online, and distributed in person (via mobile iPad device) and by e-mail list servers. The survey was given in-person at Lā ʻUlu, an annual breadfruit festival on Maui; the online survey was accessible from September to December 2018.

Data was exported and cleaned in Microsoft Excel 14.0 (Redmond, WA) and parsed. Open ended questions were reduced to a common code for quantitative analysis. Statistical analyses were conducted in JMP Pro 14 (Cary, NC). Summary statistics and distributions were carried out. Correlations, determined by one-way ANOVAs, chi-squared tests, and t-tests, focused on two variables of consumption: breadfruit consumed per serving and servings consumed per year. The results of in-person administration and online participation showed no significant differences in any response category and therefore combined results are presented.

4.3 Results

A. Consumer demographics

A total of 238 people participated in this survey, though number of responses varied per survey item.. Of respondents, the largest representations were Caucasian (59.1%), native Hawaiian (43.0%), and Asian (39.2%) (Table 8). 21.5% of all respondents were of multi-ethnic backgrounds, which is a suitable value to reflect the State demographics that estimate about 24% of the populous to be two or more ethnicities (US Census Bureau, 2018). Most participants ranged from 20 to 39 years old and 35.6% of all respondents claimed to hold a Bachelor's degree. Oʻahu residents represented the largest percentage of participants, 27.0% from Hawaiʻi island, and the continental U.S., and Maui Island each comprising about 20% of the sample size. Other islands and locations represented less than 10% of the whole. Overall demographics match well with state census data, indicating that survey participants generally represented the state population (US Census Bureau, 2018).

B. Frequency and quantity of consumption

Participants were asked to estimate how often they ate breadfruit per week, month and year. From this, total yearly consumption was estimated as a continuous variable. Overall participants ate an average of 13.7 servings of breadfruit per year but exhibited a large standard deviation (23.3) and a distribution that closely followed an exponential decline (Figure 4). Vast majority of consumers (~85%) eat breadfruit less than 20 times per year and, in fact, most (~57%) consume breadfruit less than 3 times per year. However, there are few consumers that eat breadfruit as a primary staple (up to 175 times per year) and pull the average up considerably. A second question asked consumers to estimate how much breadfruit was eaten in a single sitting. Of those who responded, consumers ate, on average, approximate one-quarter of a breadfruit per serving (22.5%) and closely followed a normal distribution, with a maximum reported consumption of $5/8^{ths}$ (62.5%) of an entire fruit (Figure 5).

C. Preparation methods

Open ended response to preparation methods indicated a range of culinary preparation, which were simplified into 11 preparation methods (see Table 9). For instance, sautéed was simplified into a form of frying. The most common cooking methods indicated were steamed (68.5%), baked (57.6%) and fried (52.3%). A number of traditional preparation methods were also reported, including *imu*, *pūlehu*, and *poi* (see Table 9 for translations). A linear regression showed a significant relationship between number of servings consumed per year and total number of preparation methods employed (r^2 =0.15, p=0.0001) (Figure 6).

D. Fruit sourcing

Respondents indicated that they obtained fruit from a number of sources, including a friend's or family's tree (63.2%), farmer's market (28.6%), their own tree (27.7%), farm-direct (12.7%), restaurant (11.4%), retail store or supplier (6.4%), or wild-picked (5.0%). Respondents were allowed to choose multiple sources if applicable; interestingly, 41.4% (n=220) of consumers indicated multiple sources (2+) for their breadfruit (Table 10). Treating fruit source as a category, tree ownership significantly increases consumption (ANOVA r^2 0.18, p<0.0001) by nearly 400% from a mean of 7.9 to 30.6 servings per year. A linear regression also indicated that the number of sources a consumer obtains fruit from was significantly correlated to the amount of breadfruit servings eaten per year (r^2 0.07, $p<0.0001$) (Figure 6).

E. Consumer awareness of health benefits

In a yes or no question, 43.2% of people indicated that he or she was aware of health benefits associated with breadfruit. An open-ended question indicated a range of self-assessed benefits that we categorized into glycemic index (4.3%), nutrition (12.0%), fiber (7.3%), protein (3.4%) and carbohydrates (12.4%). Significantly more breadfruit is eaten per year (ANOVA; r^2 0.09, $p<0.0001$) in the group that is aware of health benefits compared to those who indicate they are unaware of any specific benefits, associated with more than double the average annual servings from 7.2 to 15.6 servings per year (Figure 6).

4.4 Discussion

This survey primarily examined breadfruit consumption, both serving size and servings per year, based on demographics, preparation methods, fruit sourcing, and awareness of health benefits. Our results show correlation, although not necessarily causation, between several important categories and breadfruit consumption that we discuss here.

A. Consumption per Serving

There were no correlations between serving size of breadfruit and any variable developed from survey responses. This indicated that, for the most part, the amount consumers eat in a single sitting is not influenced by demographics, preparation, sourcing of breadfruit, or awareness of health benefits. Unlike a prior study by Roberts-Nkrumah and Badrie (2005), where an increase in serving size was correlated with frequency of consumption, we did not see any relationship between the amount of breadfruit consumed per serving and number of servings consumed per year. Average consumption was ~22% of a whole breadfruit, closely approximating a standard curve. According to the Hawaiʻi ʻUlu Producers Cooperative, currently the largest wholesaler of breadfruit in Hawaiʻi, the two most common breadfruit varieties in Hawaiʻi are the Hawaiian ʻUlu and Maʻafala, which weigh on average 3-4 and 2-3 pounds respectively (Dana Shapiro, personal communication, February 15, 2018). Furthermore, processing, which involves discarding the skin and core, removes 14-34% of the total weight of the fruit. With an average weight of 1360 g and 25% loss (341 g) in processing, this amounts to an average serving size of 224 g wet weight. Applying an average drying ratio of 0.32 (Jones et al., 2011a), this equates to 71 dry grams. While this is an initial and crude measurement, it gives an initial estimate of an average serving size portion of breadfruit.

B. Fruit Sourcing

The largest effect on frequency of consumption was seen from those who grow their own breadfruit, which potentially increased consumption nearly four-fold. Furthermore, because the largest number of respondents (58.4%) indicated that they source fruit from a friend or family member's backyard tree, owning a tree not only suggests greater consumption for the grower but may also indicate increased consumption for their friends and relatives. Suggested extrapolations from these results could begin with the positive impact of potential breadfruit tree give-aways by state or community organizations.

For instance, the Plant a Tree of Life - Grow 'Ulu project (PATOL) was initiated by the Breadfruit Institute at the National Tropical Botanical Garden in October of 2012 with three years of funding from the Ceres Trust and supplemental funding during 2013 from the Kaulunani Urban and Community Forestry Grant program (State of Hawaii Department of Land and Resources, Division of Forestry and Wildlife, http://dlnr.hawaii.gov/forestry/lap/kaulunani/, 2018). The program worked with several communities and individuals, and over 200 organizations throughout the state to distribute 10,480 breadfruit trees (Lysak et al., 2018). A recent study examining the establishment success of trees in the program indicated that 67% of the planted trees are growing optimally in their location (Lysak et al., 2018). Combined with our results, this indicated that the Plant a Tree of Life program may result in 154,000 more servings of breadfruit being eaten in Hawai'i each year by the tree owners, with additional impacts on their friends and family.

Accessibility to a breadfruit source was commonly expressed as an issue in comment boxes throughout the survey, with statements such as "I would eat more if I could get it". As stated in the results, the amount of sources accessible to participants is positively correlated with increased consumption. This correlation may be driven in both directions: the more an individual has access to breadfruit the more they consume; conversely, the more people want to consume breadfruit the more sources they may need to identify. However, there are insights that can be derived from the response data.

Seventy-one percent of respondents get their breadfruit from a backyard tree (either their own or the tree of a friend/family member), while only 5.9% get their fruit from a store or retail outlet. This huge disparity could be expected as very few stores in Hawai‘i can be seen to carry breadfruit. Even farmer's markets play a much larger role than stores, with 26.5% of respondents acquiring fruit from this source. Therefore, market improvements can be made throughout the Hawaiian islands to address this issue.

Currently, a co-op on Hawai‘i island works to wholesale breadfruit between farmers and market outlets, but as of yet do not sell to retailers. Other sites on different islands still function within a community framework: trading the fruit for other goods, selling it by the pound on-site, or processing it to create value-added products such as flour or *poi ‘ulu* (see Table 10 for translation). These systems should remain intact, however, improvements can be made in retail aspects with the support of infrastructure and storage research. Based on general comments and results, it appears that retail access to the fruit would greatly increase consumption in Hawai‘i.

C. Consumer Knowledge and Education

As many previous studies have shown, consumer knowledge appears to play a role in consumption. Educational strategies to improve consumer awareness of nutrition and cooking methods, may be determined with a basic understanding of consumer behavior, which is heavily influenced by individual attitude, self-identification and past associations, among other factors (Demartini et al., 2019; Lysak et al., 2018). Therefore, education would be most effective if it stimulates positive attitudes toward health and well-being and relates to both traditional and modern-day breadfruit usage and cultivation. In this study, heightened awareness of health benefits correlated with an increase in consumption. Overall, the health benefits that were expressed were rather general and, in some cases, not necessarily a health benefit rather than a statement of what type of food it was.

For example, when asked about specific health benefits several respondents inputted "source of carbohydrates." While this is a true statement and breadfruit is high in carbohydrates, it does not present any indication of why it is a good source of carbohydrates. Other respondents demonstrated a more in depth range of knowledge with responses such as "has a moderate glycemic index" or "is a source of high quality protein." As such, we feel that without more probing questions into the health benefits, our assessment may have examined *perception* of health benefits rather than awareness of health benefits. Workshops and educational opportunities for community members to learn about breadfruit nutrition should be more prevalent in the islands as overall awareness is relatively low – less than 50% of people are aware of health benefits of breadfruit.

In agreement with a previous study (Roberts-Nkrumah and Badrie, 2005), the two most common preparation methods were steaming and baking. In addition, the more preparation methods respondents indicated correlated with them consuming more breadfruit (Figure 6). This could be framed in two ways: those who are consuming more breadfruit are learning more ways of preparing it, or the more ways you know how to prepare it, the more breadfruit you eat. Presently there are no case studies that reflect positive impact of culinary and health courses for breadfruit specifically, however studies have been conducted that attest to communal benefits in improved diet by the intervention of educational courses in food preparation and nutrition (Reiks et al., 2014; Wrieden et al., 2007). In either perspective of consumption patterns, education in creative and traditional breadfruit preparation would further encourage consumption.

Another encouragement to breadfruit integration and consumption is Hawai'i's unique cuisine and diversity in tropical agriculture. This pair creates a niche for local chefs to build their career within the islands. Whether in high-end cuisine or street food, locally produced food is in high demand. With this growing trend, it is important that a thriving relationship between farmer and chef is maintained, as one tends to support the other. Two community colleges on O'ahu and Maui have been taking advantage of this by implementing agricultural aspects into culinary curriculum.

Kapi'olani Community College (KCC) and Maui Community College (MCC) provide culinary programs that allow students to engage in local food sourcing, food preparation, and nutrition (Culinary Arts Program, KCC, 2019). Programs include several initiatives for health and wellness and sustainability in local communities. These include improving public school meals, publishing nutritious recipes free to the public, collaborating with community organizations, and implementing sustainable food preparation and waste strategies on campus (Culinary Arts Program, KCC, 2019). These two programs have made big steps in curriculum development that could potentially be interjected into the University of Hawai'i at Manoa's food science (Food Science and Human Nutrition, FSHN) and tropical agriculture departments (Tropical Agriculture and the Environment, TAE), which are two separate entities.

Eight years ago, Syracuse University began building a food studies program that addresses this trifecta of agriculture, food nutrition and community well-being, and provide the framework for intensive study by interested students and faculty (Weissman et al., 2011). Though there is no literature that shows particular gaps of knowledge between FSHN and TAE, there may be room for an intermediate program of study that pulls from both knowledge bodies with the intention of connecting communities with locally-sourced nutritious foods.

4.5 Conclusion

The purpose of this study was to examine consumer behavior in dealing with breadfruit, considering variables that may or may not impact its consumption by Hawaiʻi residents. Survey dispersion by way of online and in-person methods made no significant difference in the results. After anaylsis, location of residency and educational background of participants both had no effect on per meal and per year consumption of breadfruit. Positive correlations were made between owning a breadfruit tree and per year consumption, as well as being aware of health benefits associated with breadfruit, and per year consumption. A two way correlation was determined between consumption and multiple methods of preparation. Based on these results and respondent comments, accessibility to breadfruit sources is also an issue in Hawai'i.

This survey could be improved by selecting more specific questions, perhaps similar to that of Roberts-Nkrumah and Badrie (2005), for respondents such as awareness of particular cultivars, or willingness to attend a grower's workshop or educational breadfruit culinary class. More research can be conducted in the development of labelled nutritional information and serving size to improve accessibility and bring the crop to more local markets and grocery stores.

Chapter 5

Conclusions

Environmental Effect on Breadfruit Nutrition, and Breadfruit's Effect on People

The global and local (Hawai'i) studies comprising this thesis research examined the role of environmental variables in breadfruit nutritional qualities. The interactions between abiotic factors and plant physiology have been investigated on a crop to crop basis for example in strawberries, tomatoes, bananas, papayas, and others, however have not been explored for breadfruit. From this research we know that, at least, precipitation and cation exchange capacity in soil are influential variables to nutritional qualities of breadfruit. The globally comprised breadfruit nutritional studies did however present some confounding factors that possibly imply the overall immature state of research that is being conducted for breadfruit in general.

Most of these studies did not report the cultivar type of the breadfruit used in sampling; as discussed in Chapter 3, and supported by Jones et al. (2010) and Ragone and Cavaletto (2006), cultivar plays a large role in nutritive aspects of the fruit. Although there is some evidence that supports cultivar adaptation to place, with regard to seasonality (Jones et al., 2013), which could have implications for adaptations reflected in nutritional qualities, this has not fully been investigated yet and cultivar type nonetheless has a significant impact on determining nutritional qualities. Another attribute of the fruit that can be further studied and is a confounding factor in this research is determining stage of maturity for fruit.

Currently, there is not standardized method or scale by which researchers can report the maturity level of breadfruit and thus it is often referred to with vague descriptors such as 'ripe' or 'mature' or 'very mature'. If these components, which can be heavily impactful to nutritional values of breadfruit, can be addressed and implemented, future analyses can control better for variation and narrow in on specific information such as nutrition among one cultivar grown in different places.

An initial look into the theme of nutritional qualities and environmental variables for Hawaii displayed similar implications to that of the global examination, with some differences. As the results showed, the greater correlations with nutritive aspects occurred among the combination of soil and climate characteristics, rather than with one or the other alone. We can conclude that in Hawaii's case, perhaps farmer management practices, which are essentially interjections of manmade environment, are playing a larger role than the natural environment. For some participating farms and farmers, this was the first time their soil and or fruit have been analyzed for their characteristics. For others, this opportunity may have been an update; all of the laboratory results were given back to the participant for their own keeping. It is important to continue to provide farmers around the world with this type of practical information, as well as challenge researchers to be as thorough as possible with gathering management practices in order to best serve communities.

Among the trifecta of variables that are known to matter in determining nutritional quality of breadfruit, we have addressed just the aspect of abiotic factors and have touched upon cultivar influence. Even so, these areas of study can be examined further and farmer practice can certainly be investigated with the intent of better understanding breadfruit physiology as a whole. In order to aid in topics of diabetes mitigation, just as Turi et al. (2015) have discussed, the resistant starch content and glycemic index of breadfruit grown in Hawaii should be further investigated and for more than one cultivar.

Following the first documented consumer survey for breadfruit consumption in Hawaii, we see a niche for research in consumer habits and behavior for Hawaii residents. The island landscape presents physical and political limitations however current leaders have made it clear that agricultural improvements and sustainability are priorities. It is an opportune time, therefore, to implement aspects of diversified cropping systems that encourage land-use efficiency and further diversity in diets of local people. Based on this survey it is clear that access to breadfruit can be improved, and that perhaps the largest contributor to overall consumption, maybe access as well, is having a tree. Education in health awareness and cooking methods for breadfruit could also impact consumption as well, which can be tools for health professionals in addressing diabetes and other lifestyle diseases that breadfruit can help to combat.

Impacts of these studies have reached beyond the numerical results. Research in breadfruit should continue in order to support efforts near and abroad that intend to enhance human well-being and access to nutritional foods, especially as society goes forward into a drastically changing environment and with it, continually changing culture and diets.

References

Abbas, F., H.M. Hammad, S. Fahad, A. Cerda, M. Rizwan, W. Farhad, S. Ehsan, and H.F. Bakhat. (2017). Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. *Environmental Science and Pollution Research 2017, 24(12), 11177-11191.*

Albrecht, A. and S.T. Kandji. (2003). Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems and Environment, 2003, 99, 15-27.*

Alscher, R.G., N. Erturk, and L.S. Heath. (2002). Role of superoxide dismutases (SODs) in controlling oxidative stress in plants. *Journal of Experimental Botany 2002, 53(372), 1331-1341.*

Appiah, F., I. Oduro, and W.O. Ellis. (2016). Nutritional composition of breadfruits (*Artocarpus* spp. and *Treculia africana*) in Ghana. *Acta horticulturae, 1128, 15-20. DOI 10.17660.*

Aurore, G., J. Nacitas, B. Parfait, and L. Fahrasmane. (2014). Seeded breadfruit naturalized in the Caribbean is not a seeded variety of *Artocarpus altilis*. *Genetic Resources and Crop Evolution 2015, 61(5), 901-907.*

Avant, S. (2013). Breadfruit Not So Appetizing to Mosquitoes. *Agricultural Research, 2013, 61(10), 11.*

Baba, S., H.T. Chan, M. Kezuka, T. Inoue, and E.W.C. Chan. (2016). *Artocarpus altilis* and *Pandanus tectorius*: Two important fruits of Oceania with medicinal values. *Emirates Journal of Food and Agriculture, 2016, 28(8), 531-539.*

Beckles, D.M. and M. Thitisaksakul. (2013). How environmental stress affects starch composition and functionality in cereal endosperm. *Starch 2014, 66, 58-71.*

Broomes, J., N. Badrie, and L. Roberts-Nkrumah. (2009). Effect of cultivar and maturity on yield and nutrient composition of breadfruit (*Artcocarpus altilis*) flour. *Proceedings of the Caribbean Food Crops Society 2009, 45, 128-135.*

Cakmak, I. (2005). The role of potassium in alleviating detrimental effects of abiotic stresses in plants. *Journal of Plant Nutrition and Soil Science 2005, 168, 521-530.*

Cao, K.F., Y.H. Guo, and Z.Q. Cai. (2006). Photosynthesis and antioxidant enzyme activity in breadfruit, jackfruit and mangosteen in southern Yunnan, China. *Journal of Horticulture Science Biotechnology, 81 (1), 168-172.*

Clark, C.J., G.S. Smith, and I.M. Gravett. (1989). Seasonal accumulation of mineral nutrients by tamarillo 2. Fruit. *Scientia horticulturae, 40(3), 203-213.*

Crisosto, C.H., V. Bremer, L. Ferguson, and G.M. Crisosto. (2010). Evaluating Quality Attributes of Four Fresh Fig (*Ficus carica* L.) Cultivars Harvested at Two Maturity Stages. *HortScience 2010, 45(4), 707-710.*

Culinary Arts Program, Kapi'olani Community College. (2019). Initiatives: Health & Wellness, and Sustainability. Retrieved February 11, 2019, from http://culinary.kapiolani.hawaii.edu/

Deivanai, S. and S.J. Bhore. (2010). Breadfruit (*Artocarpus altilis* Fosb.) – An Underutilized and Neglected Fruit Plant Species. *Middle-East Journal of Scientific Research 2010, 6(5), 418-428.*

Demartini, E., E.D Marchi, A. Cavaliere, S. Mattavelli, A. Gaviglio, A. Banterle, J. Richetin, and M. Perugini. (2019). Changing attitudes towards healthy food via self-association or nutritional information: What works best?. *Appetite, (132) 166-174*.

Dinesh, M.R. and B.M.C. Reddy. (2012). Physiological Basis of Growth and Fruit Yield Characteristics of Tropical and Sub-tropical Fruits to Temperature. *Bioversity International, Tropical Fruit Tree Species and Climate Change, 45-70.*

Office of Planning, Department of Business Economic Development & Tourism. (2012). Increased Food Security and Food Self-Sufficiency Strategy.

FAO. (2009). "International Treaty on Plant Genetic Resources for Food and Agriculture," 56. http://www.fao.org/3/a-i0510e.pdf.

Fischer, S., T. Hilger, H.P. Piepho, I. Jordan and G. Cadisch. (2019). Do we need more drought for better nutrition? The effect of precipitation on nutrient concentration in East African food crops. *Science of the Total Environment, (658) 405-415*.

Giambelluca, T.W., Q. Chen, A.G. Frazier, J.P. Price, Y.-L. Chen, P.-S. Chu, J.K. Eischeid, and D.M. Delparte. (2013). Online Rainfall Atlas of Hawai'i. *Bull. Amer. Meteor. Soc.* 94, 313-316, doi: 10.1175/BAMS-D-11-00228.1.

Giambelluca, T.W., X. Shuai, M.L. Barnes, R.J. Alliss, R.J. Longman, T. Miura, Q. Chen, A.G. Frazier, R.G. Mudd, L. Cuo, and A.D. Businger. (2014). Evapotranspiration of Hawai'i. Final report submitted to the U.S. Army Corps of Engineers—Honolulu District, and the Commission on Water Resource Management, State of Hawai'i.

Graham, H.D., and E.N. De Bravo. (1981). Composition of the Breadfruit. *Journal of Food Science 1981, 46, p535-539.*

Hasanuzzaman, M., K. Nahar, and M. Fujita. (2013). Extreme Temperature Responses, Oxidative Stress and Antioxidant Defense in Plants. *InTechOpen, Abiotic Stress – Plant Responses and Applications in Agriculture, Chapter 6, 169-205.*

Hawaii Population. (2019). Retrieved 2019-06-02, from http://worldpopulationreview.com/states/hawaii/.

Jones, A.M.P., S.J. Murch, and D. Ragone. (2010). Diversity of Breadfruit (*Artocarpus altilis*, Moraceae) Seasonality: A Resource for Year-Round Nutrition. *Economic Botany 2010, 64(4), 340-351.*

Jones, A.M.P., D. Ragone, K. Aiona, W.A. Lane, and S.J. Murch. (2011a). Nutritional and morphological diversity of breadfruit (*Artocarpus,* Moraceae): Identification of elite cultivars for food security. *Journal of Food Composition and Analysis 2011, 24, 1091-1102.*

Jones, A.M.P., D. Ragone, N.G. Tavana, D.W. Bernotas, and S.J. Murch. (2011b). Beyond the Bounty: Breadfruit (*Artocarpus altilis*) for food security and novel foods in the 21st Century. *Ethnobotany Research & Applications 2011, 9, 129-149.*

Jones, A.M.P, S.J. Murch, J. Wiseman and D. Ragone. (2013). Morphological diversity in breadfruit (*Artocarpus*, Moraceae): insights into domestication, conservation, and cultivar identification. *Genetic Resources and Crop Evolution 2013, 60, 175-192.*

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforestry Systems 2009, 76(1), 1-10.*

Kaholokula, J.K., C.T. Ing, M.A. Look, R. Delafield and K. Sinclair. (2018). Culturally responsive approaches to health promotion for Native Hawaiians and Pacific Islanders. *Annals of Human Biology, 2018, 45(3), 249-263.*

Kuti, J.O., and H.B. Konuru. (2005). Effects of genotype and cultivation environment on lycopene content in red-ripe tomatoes. *Journal of the Science of Food and Agriculture 2005, 85, 2021-2026.*

Leng, P., B. Yuan, and Y. Guo. (2014). The role of abscisic acid in fruit ripening and responses to abiotic stress. *Journal of Experimental Botany 2014, 65(16), 4577-4588.*

Lincoln, N. and T. Ladefoged. (2014). Agroecology of pre-contact Hawaiian dryland farming: the spatial extent, yield and social impact of Hawaiian breadfruit groves in Kona, Hawai‘i. *Journal of Archaeological Science, (49), 192-202.*

Lincoln, N.K. and P. Vitousek. (2017). Indigenous Polynesian Agriculture in Hawai‘i. *Oxford Research Encyclopedia of Environmental Science, 1-46. DOI: 10.1093/acrefore/9780199389414.013.376*

Lincoln, N.K., D. Ragone, N.J.C. Zerega, L.B. Roberts-Nkrumah, M. Merlin, and A.M.P. Jones. (2018). Grow Us Our Daily Bread: A Review of Breadfruit Cultivation in Traditional and Contemporary Systems. *Horticultural Reviews 2019, 46, 299-384.*

Liu, Y., A.M.P. Jones, S.J. Murch, and D. Ragone. (2014). Crop productivity, yield and seasonality of breadfruit (*Artocarpus* spp., Moraceae). *Fruits 2014, 69, 345-361.*

Liu, Y., D. Ragone, and S.J. Murch. (2015). Breadfruit (*Artocarpus altilis*): a source of high-quality protein for food security and novel food products. *Amino Acids 2015, 47(4), 847-856.*

Look, M.A., M.K. Trask-Batti, R. Agres, M.L. Mau and J.K. Kaholokula. (2013). “Health Disparities and Health Care Services.” In *Assessment and Priorities for Health and Well-Being in Native Hawaiians and Other Pacific Peoples*, ed. Department of Native Hawaiian Health, 9-19. Honolulu: University of Hawaii.

Lucas, M.P., and D. Ragone. (2012). Will Breadfruit Solve the World Hunger Crisis? New Developments in an Innovative Food Crop. *PIOJ Sustainable Development & Regional Planning Division 2013, 5(17).*

Lysak, M. (2018). Improving food and nutrition security through exploration of market potentials by revitalizing breadfruit as a strategy for adapting to climate change. (*unpublished dissertation*), University of Copenhagen Department of Plant and Environmental Science.

Lysak, M., D. Ragone and C. Henriksen. (2018). Are complimentary tree distributions effective as a means to increase local resources while targeting urban food security? The case of breadfruit in the Hawaiian Islands. (*in peer review*).

Mahmood, T., F. Anwar, M. Abbas, and N. Saari. (2012). Effect of Maturity on Phenolics (Phenolic Acids and Flavonoids) Profile of Strawberry Cultivars and Mulberry Species from Pakistan. *International Journal of Molecular Sciences 2012, 13, 4591-4607*

McCoy, M.D., M.W. Graves, and G. Murakami. (2010). Introduction of Breadfruit (*Artocarpus altilis)* to the Hawaiian Islands. *Economic Botany, 64(4), 374-381*.

Meilleur, B.A., R.R. Jones, C.A. Titchenal, and A.S. Huang. (2004). Hawaiian Breadfruit Ethnobotany, Nutrition, and Human Ecology. *College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa: CTAHR Publications and Information Office.*

Muller, O. and M. Krawinkel. (2005). Malnutrition and health in developing countries. *Canadian Medical Association Journal, 2005, 173(3), 279-286.*

Nochera, C.L. and D. Ragone. (2016). Preparation of a Breadfruit Flour Bar. *Foods 2016, 5(37), 1-7.*

Perez-Tello, G.O., B.A. Silva-Espinoza, I. Vargas-Arispuro, B.O. Briceno-Torres, and M.A. Martinez-Tellez. (2001). Effect of Temperature on Enzymatic and Physiological Factors Related to Chilling Injury in Carambola Fruit (*Averrhoa carambola* L.). *Biochemical and Biophysical Research Communications 2001, 287, 846-851.*

Perroy, R.L., J. Melrose, and S. Cares. (2016). The evolving agricultural landscape of post-plantation Hawai'i. *Applied Geography, 2016, 76, 154-162.*

Pokhrel, A., and P. Soni. (2019). Energy balance and environmental impacts of rice and wheat production: A case study in Nepal. *International Journal of Agriculture and Biological Engineering, 12(1), 201-207.*

Porter, J.R. and M.A. Semenov. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society 2005, 360, 2021-2035.*

Ragone, D. (1997). Breadfruit *Artocarpus altilis* (Parkinson) Fosberg. Promoting the conservation and use of underutilized and neglected crops. 10. *Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy.*

Ragone, D. and C.G. Cavaletto. (2006). Sensory Evaluation of Fruit Quality and Nutritional Composition of 20 Breadfruit (*Artocarpus,* Moraceae) Cultivars. *Economic Botany 2006, 60(4), 335-346.*

Ragone, D. (2014). Breadfruit Nutritional Value and Versatility. *Breadfruit Institute of the National Tropical Botanical Garden and Hawaii Homegrown Food Network, State of Hawaii Department of Agriculture.*

Ragone, D., C. Elevitch and A. Dean. (2016). Revitalizing breadfruit in Hawaii - A model for encouraging the cultivation and use of breadfruit in the tropics. *Tropical Agriculture (Trinidad).*

Raiten, D.J. and G.F. Combs. (2019). Nutritional Ecology: Understanding the Intersection of Climate/Environmental Change, Food Systems and Health. *CAB International, Agriculture for Improved Nutrition: Seizing the Momentum, 68-80.*

Reddy, M., R. Moodley and S.B. Jonnalagadda. (2014). Elemental uptake and distribution of nutrients in avocado mesocarp and the impact of soil quality. *Environmental Monitoring and Assessment 2014, 186, 4519-4529.*

Reicks, M., A.C. Trofholz, J.S. Stand and M.N. Laska. (2014). Impact of Cooking and Home Food Preparation Interventions Among Adults: Outcomes and Implications for Future Programs. *Journal of Nutrition Education and Behavior, Vol.46 (4), 259-276.*

Roberts-Nkrumah, L.B. and N. Badrie. (2005). Breadfruit consumption, cooking methods and cultivar preference among consumers in Trinidad, West Indies. *Food Quality and Preference, Vol.16, 267-274*.

Rojas, M., F. Lambert, J. Ramirez-Villegas and A.J. Challinor. (2019). Emergence of robust precipitation changes across crop production areas in the 21st century. *PNAS Latest Articles*, https://www.pnas.org/content/116/14/6673.

Rouphael, Y., M. Cardarelli, A. Bassal, C. Leonardi, F. Giuffrida, and G. Colla. (2012). Vegetable quality as affected by genetic, agronomic and environmental factors. *Journal of Food, Agriculture & Environment, 10(3,4), 680-688.*

SabahelKhier, K.M., A.S. Hussain, and K.E.A. Ishag. (2010). Effect of maturity stage on protein fractionation, *in vitro* protein digestibility and anti-nutrition factors in pineapple (*Ananas comosis*) fruit grown in Southern Sudan. *African Journal of Food Science 2010, 4(8), 550-552.*

Sanchis, E., M. Mateos, and M.B. Perez-Gago. (2015). Effect of maturity stage at processing and antioxidant treatments on the physicochemical, sensory and nutritional quality of fresh-cut ‘Rojo Brillante‘ persimmon. *Postharvest Biology and Technology 2015, 105, 34-44.*

Shapiro pers. Comm

Shiferaw, B., B.M. Prasanna, J. Hellin, and M. Banziger. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security 2011, 3, 307-327.*

Sikarawr, M.S., B.J. Hui, K. Subramaniam, B.D. Valeisamy, L.K. Yean and K. Balaji. (2014). A Review on *Artocarpus altilis* (Parkinson) Fosberg (breadfruit). *Journal of Applied Pharmaceutical Science, 2014, 4(8), 91-97.*

Somashekhar, M., N. Nayeem, and B. Sonnad. (2013). A review on family Moraceae (Mulberry) with a focus on Artocarpus species. *World Journal of Pharmacy and Pharmaceutical Sciences, 2(5), 2614-2626.*

Storey, R. and M.T. Treeby. (2000). Seasonal changes in nutrient concentrations of navel orange fruit. *Scientia Horticulturae 2000, 84, 67-82.*

Subki, A., A.A.Z. Abidin, and Z.N.B. Yusof. (2018). The Role of Thiamine in Plants and Current Perspectives in Crop Improvement, B Group Vitamins - Current Uses and Perspectives, Jean Guy LeBlanc and Graciela Savoy de Giori, IntechOpen. https://www.intechopen.com/books/b-group-vitamins-current-uses-and-perspectives/the-role-of-thiamine-in-plants-and-current-perspectives-in-crop improvement.

Swaminathan, M.S. (1987). The promise of agroforestry for ecological and nutritional security. *Agroforestry a decade of development, International Council for Research in Agroforestry Nairobi, p25-41.*

Turi, C.E., Y. Liu, D. Ragone, and S.J. Murch. (2015). Breadfruit (*Artocarpus altilis* and hybrids): A traditional crop with the potential to prevent hunger and mitigate diabetes in Oceania. *Trends in Food Science & Technology 2015, 45, 264-272.*

US Census Bureau. (2018). Race and Hispanic Origin. Retrieved January 24, 2019, from https://www.census.gov/quickfacts/hi.

Villa-Rodriguez, J.A., F.J. Molina-Corral, J.F. Ayala-Zavala, G.I. Olivas, and G.A. Gonzalez-Aguilar. (2011). Effect of maturity stage on the content of fatty acids and antioxidant activity of 'Hass' avocado. *Food Research International 2011, 44(5), 1231-1237.*

Vincente, A.R., G.A. Manganaris, G.O. Sozzi and C.H. Crisosto. (2009). Nutritional Quality of Fruits and Vegetables. *Postharvest Handling: A Systems Approach, 2nd Edition, 58-66.*

Wall, M.M. (2006). Ascorbic acid, vitamin A, and mineral composition of banana (*Musa* sp.) and papaya (*Carica papaya*) cultivars grown in Hawaii. *Journal of Food Composition and Analysis 2006, 19, 434-445.*

Wang, Y., and M. Frei. (2011). Stressed food – The impact of abiotic environmental stresses on crop quality. *Agriculture, Ecosystems and Environment 2011, 141, 271-286.*

Weissman, E., L. Gantner and L. Narine. (2011). Building a food studies program: On-the-ground reflections from Syracuse University. *Journal of Agriculture, Food Systems, and Community Development, 2(3) 79-89*.

Wootton, M. and F. Tumaalii. (1984). Composition of Flours from Samoan Breadfruit. *Journal of Food Science, 1397(49).*

Worrell, D.B. (1994). *A study of fruit development and postharvest storage of breadfruit grown in Barbados West Indies*. (Unpublished doctoral dissertation). The University of the West Indies, Trinidad and Tobago Agriculture and Life Sciences Division, St. Augustine, Trinidad and Tobago.

Worrell, D.B, C.M.S. Carrington, and D.J. Huber. (1998). Growth, maturation and ripening of breadfruit, *Artocarpus altilis* (Park.) Fosb. *Scientia Horticulturae 1998, 76(1,2), 17-28.*

Wrieden, W.L., A.S. Anderson, P.J. Longbottom, K. Valentine, M. Stead, M. Caraher, T. Lang, B. Gray and E. Dowler. (2007). The impact of a community-based food skills intervention on cooking confidence, food preparation methods and dietary choices – an exploratory trial. *Public Health Nutrition, 10(2), 203-211*.

Zerega, N., D. Ragone, and T.J. Moley. (2005)a. Breadfruit Origins, Diversity, and Human-Facilitated Distribution in Darwin's Harvest: New Approaches to the Origins, Evolution, and Conservation of Crops. *Columbia University Press, NY, 213-238.*

Zerega, N., D. Ragone, and T.J. Moley. (2005)b. Systematics and Species Limits of Breadfruit (*Artocarpus*, Moraceae). *Systematic Botany (2005), 30(3), 603-615.*

Tables & Figures

Table 1. Studies used in meta-analysis by location and date of publishing.

Author	Date	Location	Specific Location	Latitude
Adewusi et al.	1995	Nigeria	Ile-Ife town (Osun State)	7.58760
Amusa et al.	2002	Nigeria	Ile-Ife town (Osun State)	7.58760
Appiah et al.	2011, 2014	Ghana	Republic Hall of Kwame Nkrumah University of Science and Technology, Kumasi	6.66660
Aregheore	2000	Samoa	Fugalei crop market, Apia	-13.83430
Bahado-Singh et al.	2006	Jamaica	Kingston	17.99702
Bakare et al.	2012	Nigeria	Noforija	6.59460
Bakare et al.	2012	Nigeria	Mamu	7.08460
Bakare et al.	2012	Nigeria	Ifewara	7.46700
Bakare et al.	2015	Nigeria	Ijebu, North Local Gov't of Ogun State	6.83000
Broomes	2009	Trinidad	University of the West Indies, St. Augustine	10.65000
Esuoso & Bamiro	1995	Nigeria	Oja Oba market, Akure Ondo State	7.25077
Graham & De Bravo	1981	Puerto Rico	Mayaguez (four different sites stated, not described)	18.20018
Ijarotimi and Aroge	2005	Nigeria	Akure, Ondo State local market	7.25710
Jones et al.	2011	Hawaii	Kahanu Garden, National Tropical Botanical Garden	20.79860
Leaky	1979	Carribbean	-	21.46910
Leterme et al.	2005	Columbian Andes	Cauca River Valley, rain forests of Colombian Pacific coast	3.42056
Loos et al.	1981	Puerto Rico	-	18.20018
Malomo et al.	2011	Nigeria	Akure, Ondo State local farm	7.25077
Malomo et al.	2011	Nigeria	Akure, Ondo State local farm	7.25710
Mayaki et al.	2003	Nigeria	Ile-Ife, Oshun State	7.46667
Meilleur	2004	Hawaii	Keauhou	19.57564
Meilleur	2004	Hawaii	Hilo Town	19.72410
Murai et al.	1958	American Samoa	Islet of Aunuu	-14.27810
Murai et al.	1958	American Samoa	Utulei	-14.27560
Murai et al.	1958	Caroline Islands	Tol Island, Truk District	7.36570
Murai et al.	1958	Marshall Islands	Uliga Atoll	7.09280
Murai et al.	1958	Caroline Islands	Dublon,Truk District	7.36670
Murai et al.	1958	Caroline Islands	Moen Island,Truk District	7.45000
Nacitas et al .	2009	French West Indies	Martinique	14.60890
Nelson-Quartey et al.	2007	Ghana	-	5.55602
Nochera & Caldwell	1992	Puerto Rico	Mayaguez	18.20207
Oduro	2007	Kumasi, Ghana	Kwame Nkrumah University of Science and Technology	6.66660
Oladunjoye et al.	2010	Nigeria	Ile-Ife, Osun State	7.46667
Oulai et al.	2013	Republic of Cote d'Ivoire	Abidjan	5.34530
Peters	1956	Solomons	Reef Islands	-10.25000
Ragone & Cavaletto	2006	Hawaii	Kahanu Garden, National Tropical Botanical Garden, Maui	20.79860
Ravindran & Sivakanesan	1995	Sri Lanka	local home gardens	7.87310
Reeve	1974	Puerto Rico	-	18.20018
Thompson	1914	Hawaii	Makiki Station	21.30860
Wenkam	1990	Hawaii	Lower St. Louis Heights	21.30310
Widanagamage et al.	2009	Sri Lanka	local markets	7.87310
Wootton & Tumaalii	1984	Western Samoa	Agricultural Research Station at Nafanua	-13.85600

Table 2a. Summary statistics of climate variables for all study locations.				
	Mean	**SD**	**Max**	**Min**
Elevation (m)	223.05	237.42	959.00	2.00
Vapor Pressure (kPa)	2.54	0.33	3.03	1.75
Temperature (°C)	25.64	1.78	27.71	21.00
Precipitation (mm)	1889.40	784.86	3429.00	886.00
Solar Radiation (kJ m^2 day^1)	16910.25	1687.94	19810.75	14447.67

Table 2b. Summary statistics for soil variables of all study locations.				
	Mean	**SD**	**Max**	**Min**
Cation Exchange Capacity (CEC)	20.20	12.31	60.00	6.00
Soil pH & Water	57.60	5.67	75.00	49.00
Soil Water Capacity	13.75	3.34	23.00	5.00
Soil Texture	4.75	2.75	9.00	1.00
Nutrient Availability*	1.10	1.27	7.00	0.00
Nutrient Retention**	1.10	1.23	7.00	0.00

*Soil data was derived from the Harmonized World Soil Database (HWSD). The HWSD determines "nutrient availability" using diagnostics including *texture and structure, organic carbon, pH, and total exchangeable bases. "Nutrient retention" is determined by the HWSD in using measurements of **organic carbon, texture, base saturation, cation exchange capacity (of soil and of clay fraction), and pH.*

Table 3. Summary statistics of nutritional composition for all breadfruit samples across all study sites.

	Nutritional Quality	n	Mean	SD	Max	Min
	Energy (kcl/100g)	18	209.07	111.14	393.40	103.00
(g/100g)	Water	15	68.85	6.41	83.60	59.00
	Crude Protein	27	3.60	2.26	11.40	0.60
	Actual Protein	12	3.30	2.26	7.44	0.07
	Total Protein	39	3.51	2.23	11.40	0.07
	Fat	26	1.35	1.45	4.90	0.18
	Total Fat	32	1.42	1.35	4.90	0.18
	Starch	12	59.86	22.83	80.90	9.30
	Total Carbohydrates	23	57.21	24.41	88.20	17.50
	Crude Fiber	23	4.21	2.53	9.04	0.88
	Dietary Fiber	11	3.68	2.59	8.13	0.90
	Total Fiber	34	4.04	2.52	9.04	0.88
(mg/100g)	Ash	25	2.09	1.19	3.94	0.30
	Ca	24	37.20	28.41	123.00	1.00
	P	19	73.53	56.49	188.00	1.70
	Mg	12	64.42	48.04	165.00	9.95
	Na	11	58.76	72.48	240.00	2.79
	K	12	849.40	647.70	2060.00	66.90
	Fe	20	4.44	7.90	29.00	0.26
	Zn	8	0.66	0.77	2.24	0.07
	Thiamine	9	0.11	0.06	0.22	0.07
	Riboflavin	10	0.08	0.05	0.21	0.05
	Niacin	10	1.40	0.51	2.40	0.62

Table 4a. R-squared and p-values of a multivariate analysis for nutritional values and climate variables; only significant relationships are presented.

	r^2	*P*
Energy	0.69	0.000
Protein	0.39	0.009
Fat	0.36	0.005
Starch	0.97	0.000
Carbohydrates	0.72	0.000
Fiber	0.19	0.036
Ash	0.35	0.009
Zn	0.94	0.001
Thiamine	0.98	0.000
Riboflavin	0.88	0.001
Niacin	0.74	0.009

Table 4b. R-squared and p-values of a multivariate analysis for nutritional values and soil variables; only significant relationships are presented.

	r^2	*P*
Energy	0.72	0.000
Protein	0.42	0.003
Fat	0.29	0.030
Starch	0.75	0.002
Carbohydrates	0.76	0.000
Fiber	0.44	0.000
P	0.34	0.046
Mg	0.56	0.024
Zn	0.92	0.013
Thiamine	0.97	0.001
Riboflavin	0.64	0.048
Niacin	0.89	0.035

Table 4c. R-squared and p-values of a multivariate analysis for nutritional values and all abiotic variables; only significant relationships are presented.

	r^2	*P*
Energy	0.87	0.000
Protein	0.36	0.007
Fat	0.36	0.005
Starch	0.65	0.032
Carbohydrates	0.81	0.000
Fiber	0.44	0.000
Ash	0.33	0.018
P	0.34	0.046
Fe	0.42	0.028
Zn	0.97	0.012
Thiamine	1.00	0.000
Riboflavin	0.92	0.001
Niacin	0.94	0.011

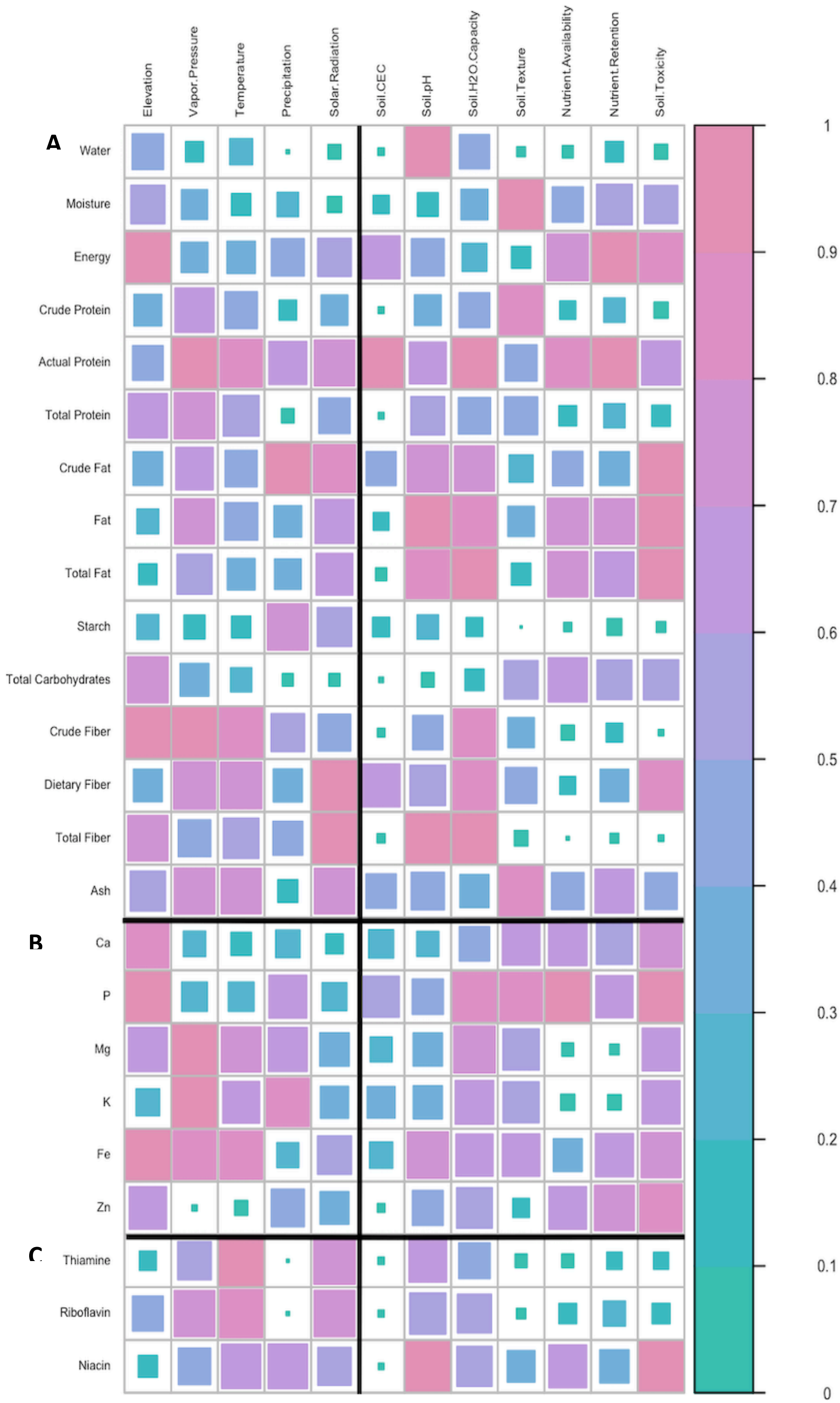

Figure 1. A correlation matrix displaying all relationships between nutritional components and abiotic (climate on the left and soil on the right) variables. Separated by categories A) proximate analysis, B) Macro-micro nutrients and C) Vitamins. Seafoam color indicates lower p-value (p<0.05 is significant), and size of square is indicative of the level of correlation (R-values).

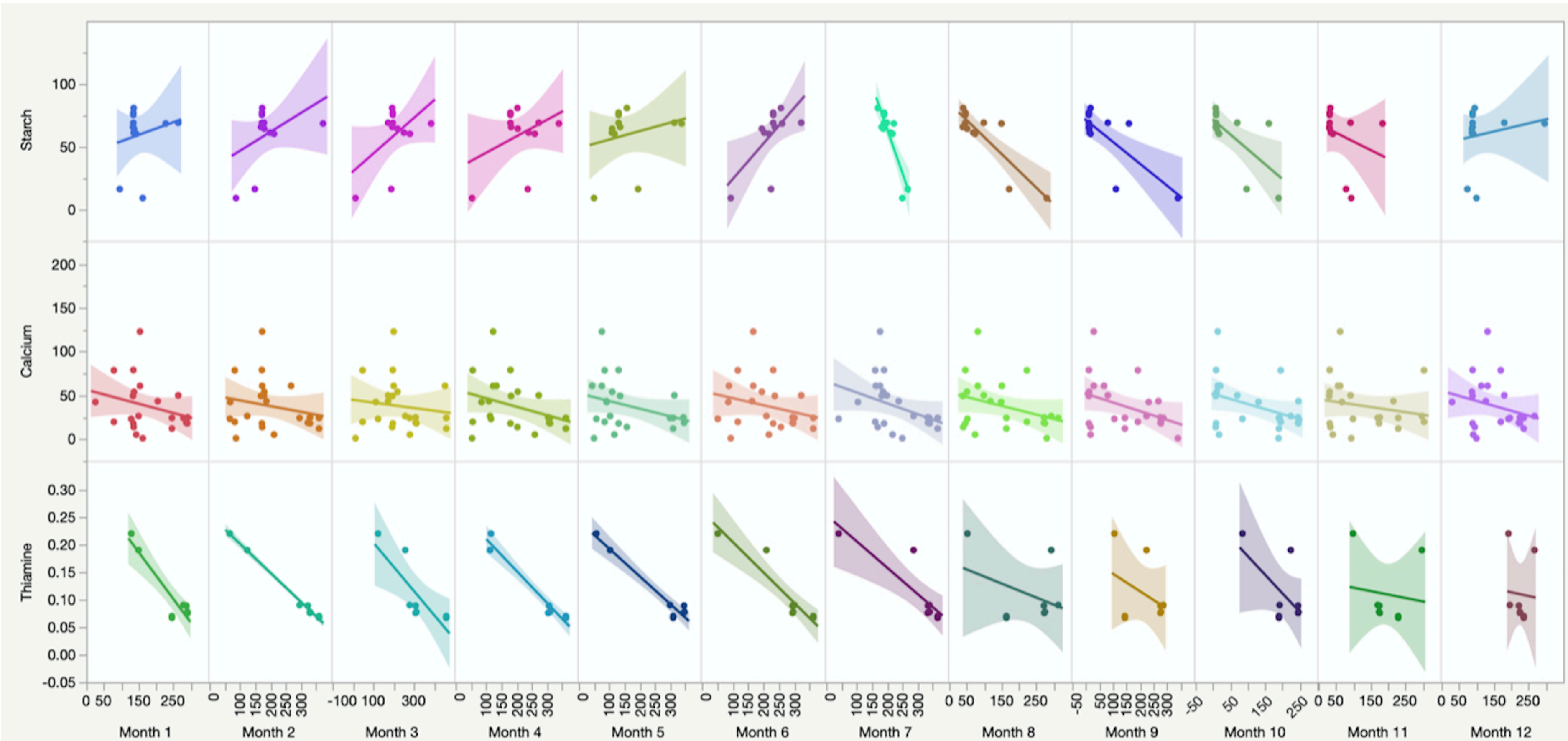

Figure 2. Three nutritional measurements are representative of each category (from top: proximate analysis, macro-micro nutrients and vitamins) in correlation to average precipitation over the course of twelve months. The regressions displayed are the general patterns for each nutritional category, as precipitation changes over time.

Table 5. Summary statistics for climate variables of participating Hawaiʻi sites.				
	Mean	**SD**	**Max**	**Min**
Potential Evapotranspiration (mm)	3220.47	1118.81	5803.87	1967.22
Rainfall (mm)	3098.68	1717.29	8219.89	628.20
Vapor Pressure Deficit (Pa)	795.81	121.86	927.50	435.35
Net Radiation (W/m^2)	129.42	11.17	153.02	102.72
Elevation (m)	92.13	101.10	438.25	3.55
Air Temperature (°C)	22.81	0.78	23.82	20.35

Table 6. Summary statistics for soil variables of participating Hawaiʻi sites.				
	Mean	**SD**	**Max**	**Min**
pH	6.17	0.81	8.20	4.60
Organic Carbon (%)	2.01	0.25	2.44	1.86
Nitrogen (%)	0.43	0.37	1.66	0.19
Total Exchange Capacity (TEC) (meq/100g)	19.19	2.24	24.22	17.92
Phosphorus (mg/kg)	77.40	106.48	605.00	4.00
Calcium (mg/kg)	2953.66	1639.29	5959.00	355.00
Magnesium (mg/kg)	764.50	480.69	1778.00	76.00
Potassium (mg/kg)	436.54	301.46	1484.00	48.00

Table 7. Multivariate analysis of climate, soil, and both sets of variables with nutritional measurements of breadfruit grown in Hawai'i.						
	Climate		Soil		Mixed	
Proximate	r^2	*P*	r^2	*P*	r^2	*P*
Energy	0.08	*0.125*	0.31	*0.001*	0.49	*0.000*
Crude Protei	0.04	*0.070*	0.31	*0.001*	0.35	*0.001*
Moisture	0.16	*0.015*	0.28	*0.001*	0.40	*0.000*
Crude Fat	0.26	*0.001*	0.21	*0.010*	0.45	*0.000*
Crude Fiber	0.40	*0.001*	0.10	*0.005*	0.40	*0.001*
Total Starch	0.31	*0.060*	0.39	*0.050*	0.39	*0.050*
Macro-Micro						
Nitrogen	0.11	*0.100*	0.32	*0.000*	0.44	*0.000*
Phosphorus	0.07	*0.150*	0.16	*0.060*	0.21	*0.030*
Magnesium	0.20	*0.002*	0.30	*0.001*	0.41	*0.000*
Potassium	0.04	*0.200*	0.24	*0.005*	0.24	*0.005*
Calcium	0.16	*0.007*	0.11	*0.010*	0.31	*0.006*
Sulfur	0.05	*0.070*	0.22	*0.010*	0.26	*0.010*
Boron	0.13	*0.050*	0.17	*0.020*	0.17	*0.020*
Iron	0.03	*0.150*	0.07	*0.070*	0.07	*0.070*
Copper	0.02	*0.290*	0.24	*0.006*	0.28	*0.007*
Zinc	0.13	*0.050*	0.29	*0.005*	0.37	*0.003*
Aluminum	0.14	*0.004*	0.09	*0.040*	0.29	*0.006*

R-squared and p-values represent degree of correlation and significance of a relationship between nutritional value and abiotoic category, if any. Climate variables within the multivariate included air temperature, rainfall, net radiation, potential evapotranspiration, vapor pressure deficit, and elevation. Soil variables included TEC (), pH, organic carbon, nitrogen, phosphorus, calcium, magnesium, and

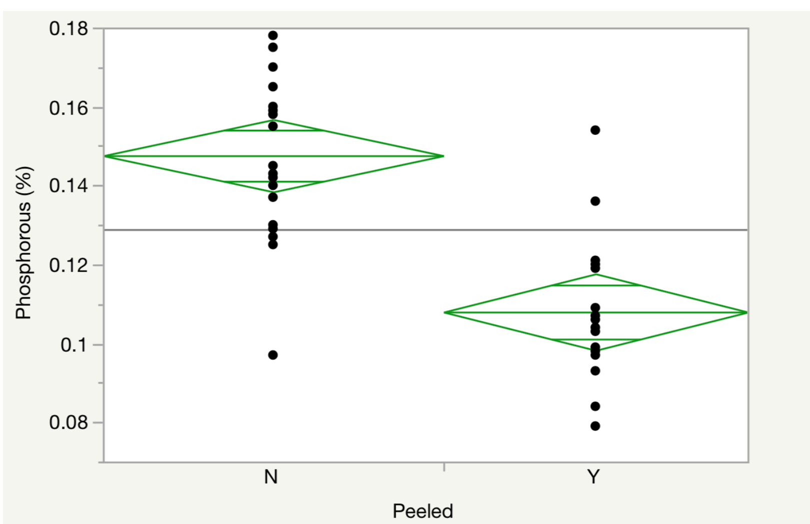

Figure 3. The effect of peel and core of breadfruit left in-tact during sampling, and that of peel and core removed during sampling. Phosphorus is representative of majority of the measured macro- and micronutrients, and the correlation between nutrient levels and peel left on. N=No; not peeled (left in-tact), Y=Yes; peeled and cored.

Table 8. Consumer demographics by percentage.

Ethnicity (*n=237*)*	**% respondents**
Native Hawaiian	43.0
Asian	39.2
Pacific Islander	10.5
White/Caucasian	59.1
Hispanic/Latino	8.0
Other	9.3
Multi-ethnic	21.5
Age (years, *n=235*)	
0-19	2.1
20-39	51.9
40-59	28.9
60-79	17.0
Education (*n=236)*	
Junior high	0.4
High school diploma/GED	7.6
Some college, no degree	12.3
Associate degree	5.5
Bachelor's degree	35.6
Master's degree	26.3
Doctorate degree	9.7
Professional degree	2.5
Residence (*n=237*)	
Hawai'i	21.9
Maui	19.4
O'ahu	27.4
Kaua'i	3.4
Moloka'i	1.3
Lana'i	0.0
Ni'ihau	0.4
Continental U.S.	20.7
Pacific Island Nation	1.7
International	3.8

*multiple answers were allowed.

Table 9. Preparation methods and the percent response reported by consumers; multiple answers were allowed.

Preparation Method	**% respondents**
Steamed	68.5
Baked	57.6
Fried	52.3
Imu'd*	14.7
Processed to flour	13.4
Boiled	4.6
Hummus	2.9
Ripe/Raw	2.5
Pulehu**/grilled	2.1
Pickled	2.1
Poi***	1.7

*imu'd = put into traditional underground oven; **pulehu = places directly on coals and charred; ***poi = cooked and mashed with water to make a paste

Table 10. Breadfruit sources and percent response indicated by consumers; multiple answers were allowed.

Breadfruit Source	**% respondents**
Grown by friend/family	63.2
Bought at farmer's market	28.6
Grown by self	27.7
Grown by farm	12.7
Bought at restaurant	11.4
Bought at supplier/retailer	6.4
Picked from wild tree	5.0
Multi-source (2+)	41.4

*consumers were allowed to pick multiple sources if applicable.

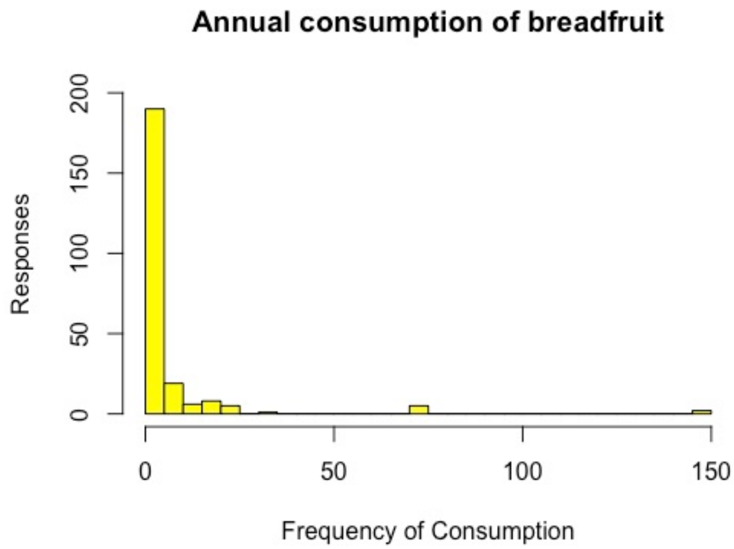

Figure 4. Reported annual consumption of breadfruit by Hawaii residents.

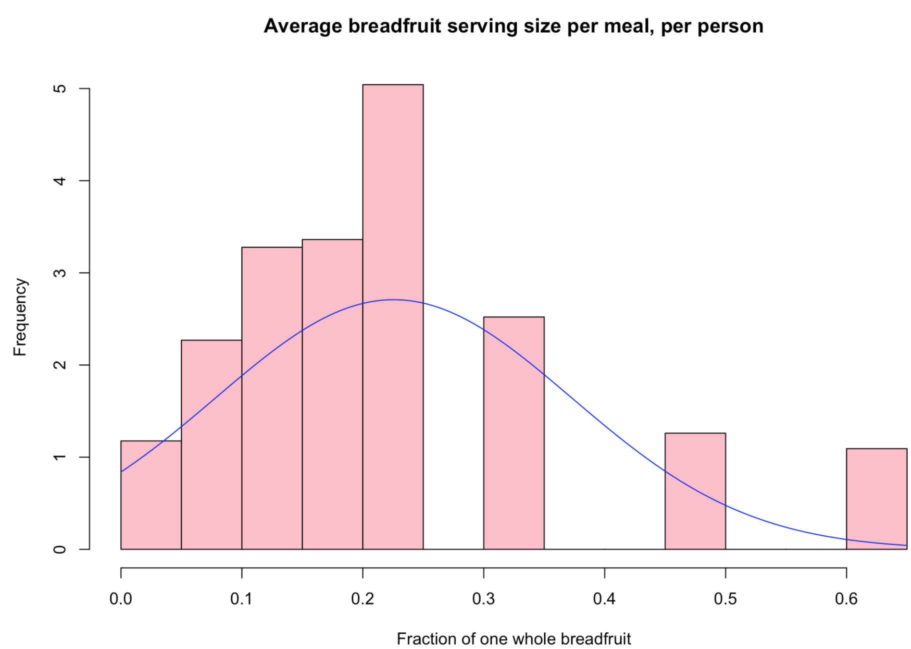

Figure 5. Reported serving sizes for breadfruit in one sitting by Hawaii residents (percentage of 1 whole breadfruit).

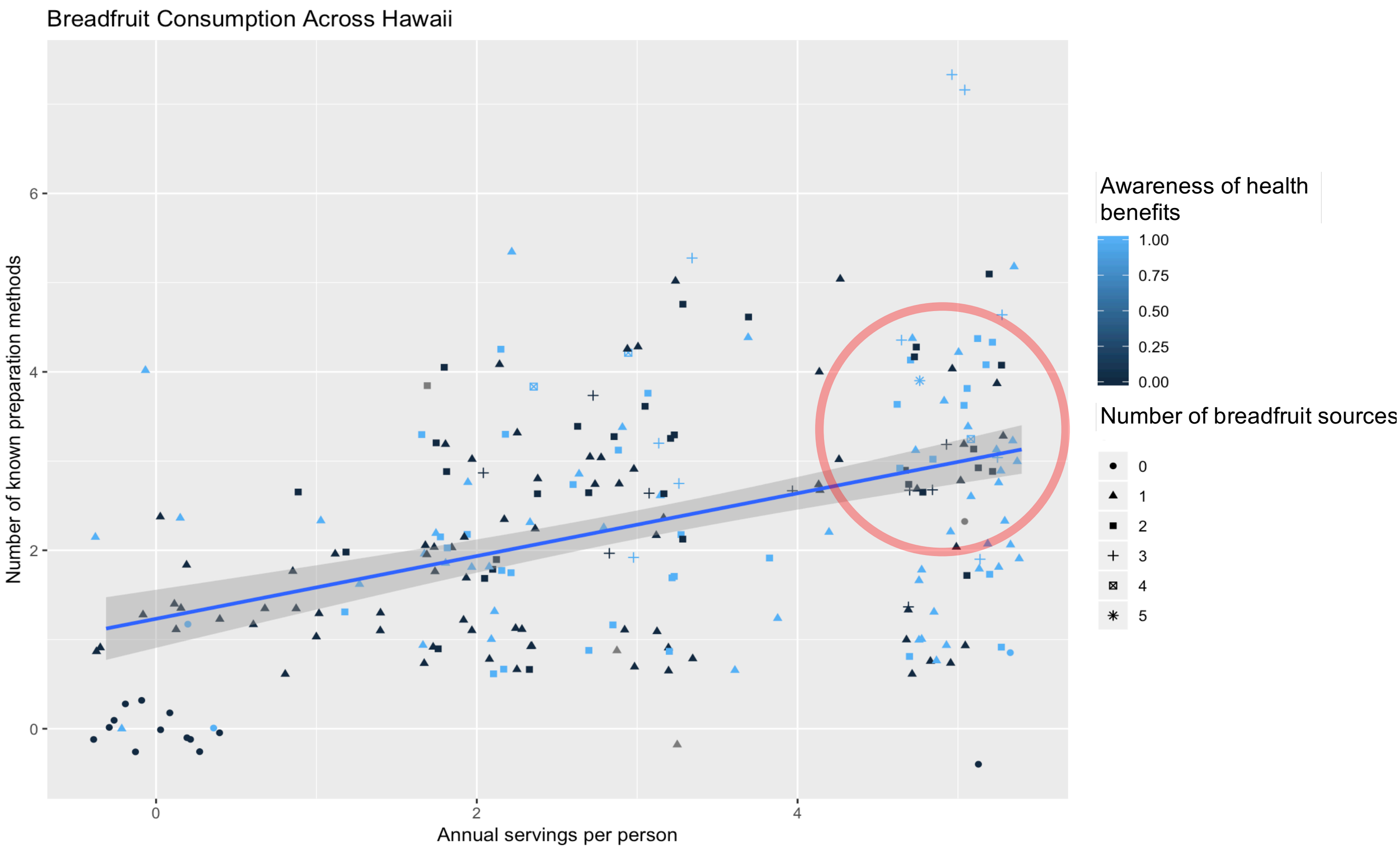

Figure 6. Annual servings of breadfruit per person by preparation methods (y-axis), health awareness (color-yes=light blue, no=black), and number of utilized sources (shape). The encircled portion of the graph focuses on the attributes of participants who are eating the most breadfruit (servings) per year; these people are aware of health benefits associated with consumption, know multiple preparation methods, and utilize one or more sources to obtain the fruit.

***There were no reports of negative servings or preparation methods. A "jitter" was applied to this graph in order to accommodate the large amount of participants and visualize as many data points as possible without compromising the regression. This is a function in R Software that adds small amounts of noise to numeric vectors which allow overlapping values to be better visualized.*